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Review of solar dryers for agricultural and marine products

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ABSTRACT

Drying for agricultural and marine products are one of the most attractive and cost-effective application of solar energy. Numerous types of solar dryers have been designed and developed in various parts of the world, yielding varying degrees of technical performance. Basically, there are four types of solar dryers; (1) direct solar dryers, (2) indirect solar dryers, (3) mixed-mode dryers and (4) hybrid solar dryers. This paper is a review of these types of solar dryers with aspect to the product being dried, technical and economical aspects. The technical directions in the development of solar-assisted drying systems for agricultural produce are compact collector design, high efficiency, integrated storage, and long-life drying system. Air-based solar collectors are not the only available systems. Water-based collectors can also be used whereby water to air heat exchanger can be used. The hot air for drying of agricultural produce can be forced to flow in the water to air heat exchanger. The hot water tank acts as heat storage of the solar drying system.

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1. Introduction

The potential of using solar energy in the agricultural sector has increased due to fluctuation in the price of fossil fuel, environmental concerns and expected depletion of conventional fossil fuels. Solar assisted drying system is one of the most attractive and promising applications of solar energy systems in tropical and subtropical countries. Traditionally all the agricultural crops were dried in the sun. Drying is one of an important post handling process of agricultural produce. It can extend shelf life of the harvested products, improve quality, improve the bargaining position of the farmer to maintain relatively constant price of his products and reduces post harvest losses and lower transportation costs since most of the water are taken out from the product during the drying process. Direct sun drying requires large open space area, and very much dependent on the availability of sunshine, susceptible to contamination with foreign materials such as dusts, litters and are exposed to birds, insect and rodents. Hence, most agricultural produce that is intended to be stored must be dried first. Otherwise insects and fungi, which thrive in moist conditions, render them unusable.

Other limitations were given by the availability of appropriate drying equipment which is technically and economically feasible and the lack of knowledge how to process agricultural products. Up to now only a few solar dryers who meet the technical, economical and socio-economical requirements are commercially available. The technical development of solar drying systems can proceed in two directions. Firstly, simple, low power, short life, and comparatively low efficiency-drying system. Secondly, high efficiency, high power, long life expensive drying system [1,2]. Various solar dryers have been developed in the past for the efficient utilization of solar energy. Many studied have been reported on solar drying of agricultural products [3,4]. Several studied have been done in the tropics and subtropics to develop solar dryers for agricultural products. Basically, there are four types of solar dryers [5]; direct solar dryers, indirect solar dryers, mixed-mode dryers, and hybrid solar dryers.

The energy requirement for agricultural products can be determined from the initial and final moisture content of each product. Products have different drying rate and maximum allowable temperatures, as given in Table 1 [6–8].

2. Classification of solar drying systems

Table 2 shows a systematic classification of available solar dryers for agricultural products, based on the design of system components and mode of utilization of solar energy.

3. Types of solar drying systems: a review

3.1. Natural convection solar dryers (passive dryers)

The simplest of solar cabinet dryer (Fig. 1) was presented by Othieno [9], it was very simple, and consists essentially of a small wooden hot box. Dimensions of this drier is 2 m $\times$ 1 m (long and width). The sides and bottom can be portable and can be constructed from wood or metal sheet. A transparent polyethylene sheet was used as cover at upper surface. Air holes are located on the sides of the drier for circulation.

Othieno [9] designed a portable direct type natural convection solar dryer (Fig. 2). It consists simply of a rectangular-shaped with transparent top and blackened interior surfaces. Clear polyethylene plastic was placed over the heating chamber to allow solar radiation to heat the air. Black polyethylene was also placed under the chamber to absorb the heat and to keep out moisture from the ground. Another black polyethylene sheet was also placed over the drying chamber to prevent bleaching. Ventilation holes were not provided along the sides but an opening in the front of the unit allowed ambient air to enter the heating chamber and another opening at the rear of the drying chamber allowed moist air to escape from the unit. This dryer could also be used as a direct dryer for crops that are not subject to bleaching if the product is placed directly into the heating chamber. In both system, the airflow is very low and, again, the improvements did not significantly improve the performance of the dryer.

Fig. 3 shows direct solar cabinet dryer fabricated and tested by Lawand [10] at the Brace Research Institute in Canada with loading of 7.5 kg/m^2 of drying area. The distance between the two layers of glazing is usually around 1 cm. In order to provide air circulation in the drier, air holes are located on the side of the drier.

Evaluation performance studies of solar cabinet dryer were reported by [11–14]. Sharma et al. [13] found that the predicted plate temperature for no load reaches a maximum of 80–85 °C during the noon hours, while with a load of 20 kg of wheat, the maximum temperature is about 45–50 °C. As well, Minka [14] reported that temperatures reached in the cabinet dryer (Fig. 4) were 20–30 °C above ambient temperature the cabinet dryer should be useful in drying a variety of foodstuff.

Gbaha et al. [15] designed a direct type natural convection solar dryer (Fig. 5) and then tested experimentally by drying cassava, bananas and mango slices. This drying is a simple design and can be manufactured by farmers from local materials. It has a relatively moderate cost and is easy to use. They reported that the thermal performance of the newly developed dryer in terms of heat and mass transfers influenced by solar incident radiation were found to

Table 1
Moisture contents of solar drying of various agricultural produces [6–8].

Product	Moisture content		Max. allowable temp. (°C)	Drying time (h)
	Initial (%)	Final (%)		
Onions	85	6	55	48
Onion flakes	80	10	55	24
Onion rings	80	10	55	
Tomatoes	95	7	60	36
Green peas	80	5	60	8–10
Grapes	80	15–20		32–40
Applies	82	11–14	65–70	24–26
Figs	70	20	70	32
Bananas	80	15	70	15
Cassava	62	17		
Copra	30	5		
Tobacco	90	10		96
Coffee	65	11		288
Garlic flakes	80	4		48
Chilies	80	5		48
Ginger	80	10		168
Cabbage	80	4	65	48
Tea	80	3		96
Pepper	71	13		48
Turmeric	80	10		120
Potato chips	75	13	70	72
Paddy, raw	22–24	11	50	
Paddy, parboiled	30–35	13	50	
Maize	35	15	60	
Wheat	20	16	45	
Millet	21	4		
Corn	24	14	–	
Rice	24	11	50	
Cauliflower	80	6	65	
Carrots	70	5	75	
Green beans	70	5	75	
Garlic	80	4	55	
Cabbage	80	4	55	
Sweet potato	75	7	55	
Red lauan	90	20		
Potatoes	75	13	75	
Spinach	80	10		
Prunes	85	15	55	
Apricots	85	18	65	
Peaches	85	18	65	
Guavas	80	7	65	
Mulberries	80	10	65	
Okra	80	20	65	
Pineapple	80	10	65	
Yams	80	10	65	
Nutmeg	80	20	65	
Sorrel	80	20	65	
Coffee	50	11	–	
Coffee beans	55	12	–	
Cocoa beans	50	7	–	
Cotton	50	9	75	
Cotton seed	50	8	75	
French bean	70	5	75	
Groundnuts	40	9	–	

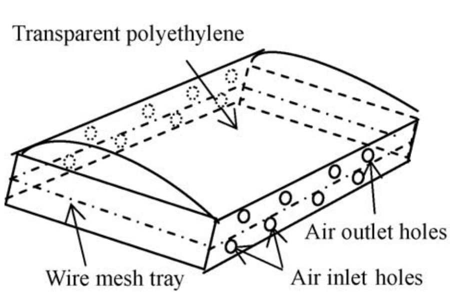
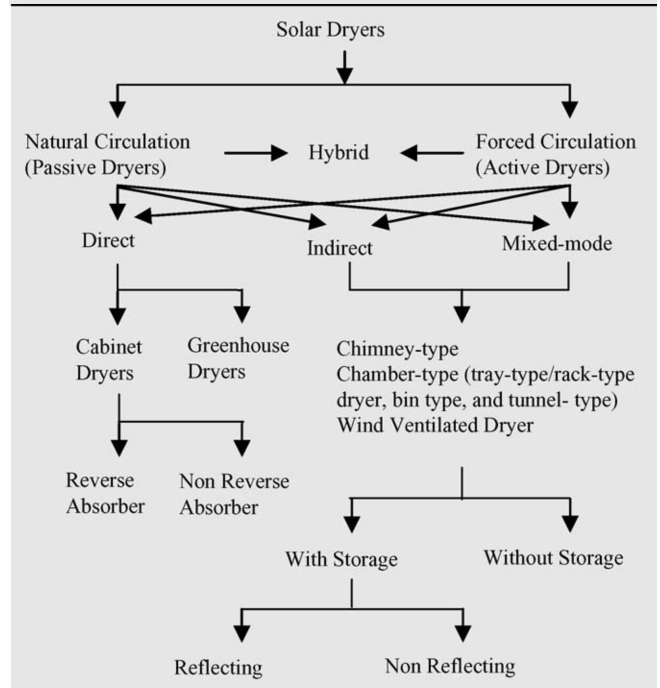


Fig. 1. Direct solar cabinet dryers (tray type) [9].

Table 2
Classification of solar dryers and drying modes.



be higher compared to open sub drying for the selected food materials.

Fig. 6 shows a small size PAU domestic natural convection solar dryer. It mainly consists of a hot box, shading, trays and base frame. The frame size 19 mm × 19 mm × 1.6 mm while the hot box was built from angle iron. A glazing transparent window glass (4 mm) was fixed as glazing. It was fixed to the hot box with an aluminium angle. In order to provide air circulation in the drier, 40 holes with

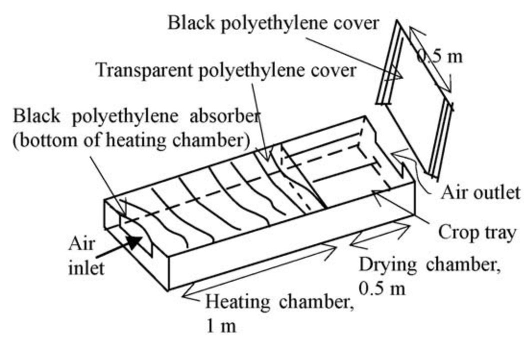
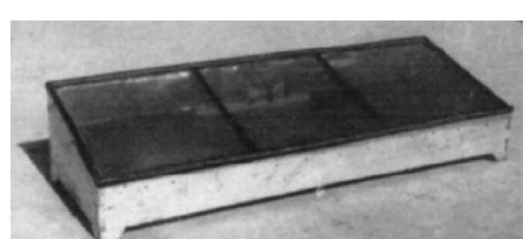


Fig. 2. Portable tray type solar dryer [9].


Fig. 3. Photograph of direct solar cabinet dryers [10].

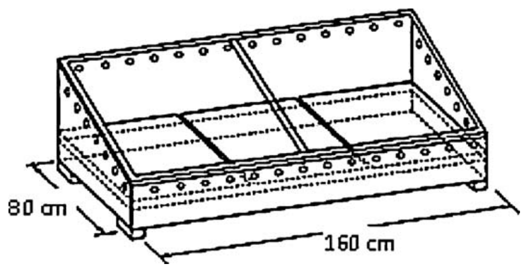


Fig. 4. Direct solar cabinet dryers [14,27].

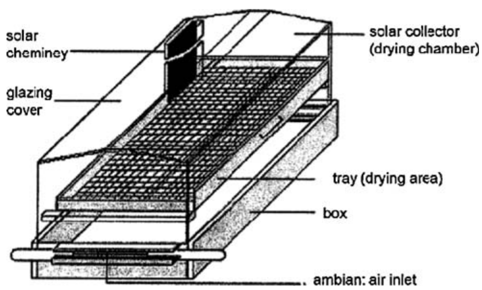


Fig. 5. Direct solar cabinet dryers [15].

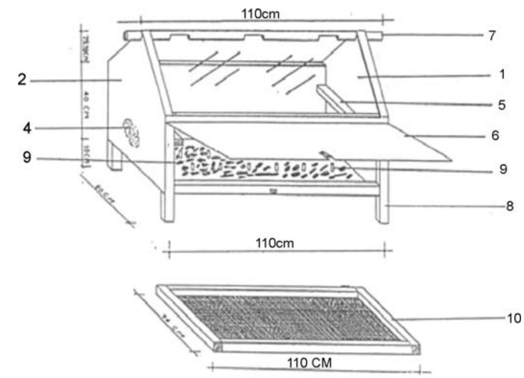


Fig. 7. Direct solar cabinet dryer (1. transparent cover/plastic, 2. bamboo for outgoing air, 3. holes of 1 in. pipe for inlet air, 4. chalcoal, 5. single tray, 6. door, 7. walla, 8. legs, 9. insulation, 10. thermometer) [17].

total area of 0.002 m^2 are located on the top side of the drier. The flat thermocol sheet of 5 cm thickness is used as the insulator.

Mursalim et al. [17] evaluated a modified cabinet dryer with natural convection system (Fig. 7). The dryer is with a single transparent plastic cover and Sawdust was used the insulator. The drying chambers walls was build of plywood painted black with dimensions 120 cm $\times$ 80 cm $\times$ 40 cm (long, width, and height). For air flow, 12 holes were providing with 1 in pipe at the bottom.

The main disadvantages of the cabinet dryer are (i) small capacity of the crop, hence cannot be used for commercial purpose, (ii) required drying time is large, (iii) due to evaporation of moisture and its condensation on the glass cover, the transmittivity of the glass cover is reduced, (iv) overheating of the crop may take place due to direct exposure to sunlight, and hence, the quality of the product may deteriorate, and (v) the efficiency is low because part of the solar energy input is used to induce airflow, and the product itself acts as an absorber [55,56]. In order to solve the above problems, various design of passive solar dryer has been developed and tested [9–37]. These designs have been recommended for commercial purposes and these include chamber-type dryer (tray-type/rack-type dryer, bin type, and tunnel type), chimney-type dyer, and wind-ventilated dryer.

Hallack et al. [18] developed a modified of solar cabinet dryer (Fig. 8). They design is easy to use and simple to construct. It has the shape of metal staircase with its base and sides covered with double-walled galvanized metal sheets with cavity filled with non-degradable thermal insulation. The upper surface is covered with a transparent polycarbon sheet to allow the sun's to pass through and be trapped. Polycarbon was used instead of glass as it is non-breakable. A chimney of 0.1 m length and 0.1 m diameter is located at the upper end of dryer to ease the flow of air. The dimensions of the dryer are fairly moderate, large enough to allow its three shelves to loading 20 kg of fruit and vegetables.

Portable indirect solar dryers also fabricated; made of wood and plywood as reported by Amouzou et al. [19]. These dryer named



Fig. 6. Photograph of PAU domestic solar dryer with door open [16].

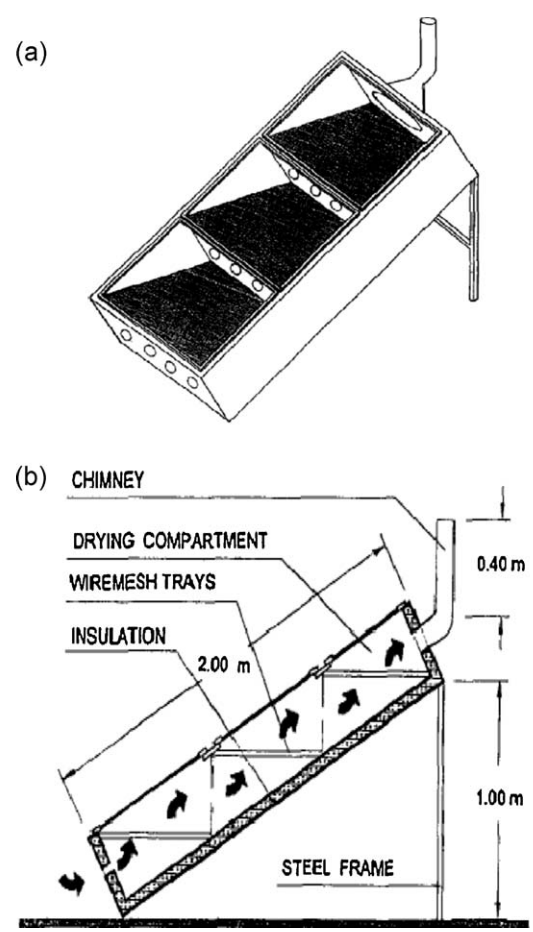


Fig. 8. Staircase type dryer: (a) general view and (b) side view [18].

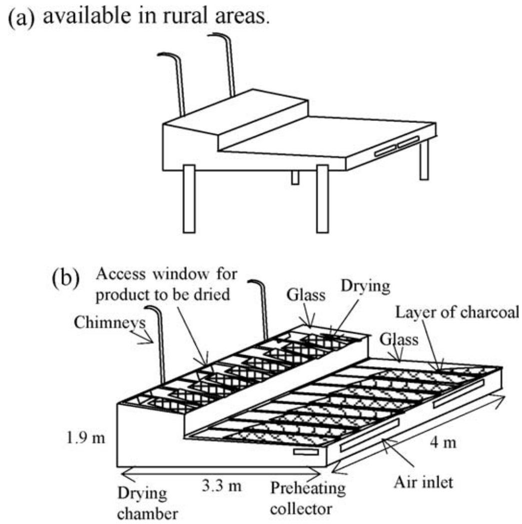


Fig. 9. (a) Brace-type wooden solar dryer. (b) Multipurpose cement solar dryer [19].

brace-type (Fig. 9a) and cement solar dryer (Fig. 9b). Brace type is 1.12 m long, 1.3 m wide, 0.67 m high, and its collector area is about 1 m^2. The absorber is made galvanized sheet metal painted black. The drying chamber can dry 10–15 kg of product in 3 days. The wooden frame was not weather-resistant (rain or wind), and the problem of waterproofing arose. Its useful life was 4 years. The multipurpose cement dryer was the same as the brace-type but made from breezeblock instead of wood. It is 4.82 m $\times$ 2.82 m and has load capacity of 80–100 kg. Both the collector for preheating the air and the drying chamber are covered with nine glass panel. To reduce the cost of the absorber, the black metal sheet was replaced with charcoal, a product that is available in rural areas.

Bolaji [20] developed and evaluated a solar dryer using a box-type absorber collector. The dryer (Fig. 10) consists of an air heater, an opaque crop bin, and a chimney. The box-type absorber collector made of a glass cover and black absorber plate was inclined at angle of about 20° to the horizontal to allow the heated air to rise up the unit with little resistance. He reported that the maximum efficiency obtained in the box-type absorber system was 60.5% while those of flat plate absorber and fin-type absorber were 21 and 36%, respectively. He calculated also the maximum average temperature inside the collector and drying chamber were 64 and 57 °C, respectively, while the maximum ambient temperature observed was 33.5 °C.

Bolaji and Olalusi [21] constructed and evaluated performance a mixed-mode solar dryer for food preservation, Fig. 11. They reported that the temperature rise inside the drying cabinet was up to 74% for about 3 h immediately after 12.00 h (noon). The drying rate and system efficiency were 0.62 kg/h and 57.5%, respectively. The rapid rate of drying in the dryer reveals its ability to dry food items reasonably rapidly to a safe moisture level. Results showed that during the test period revealed that the temperatures inside the dryer and solar collector were much higher than ambient temperature during most hours of the day-light.

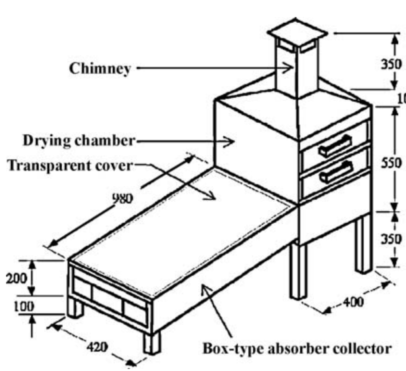


Fig. 10. Indirect natural convection solar dryer [20].

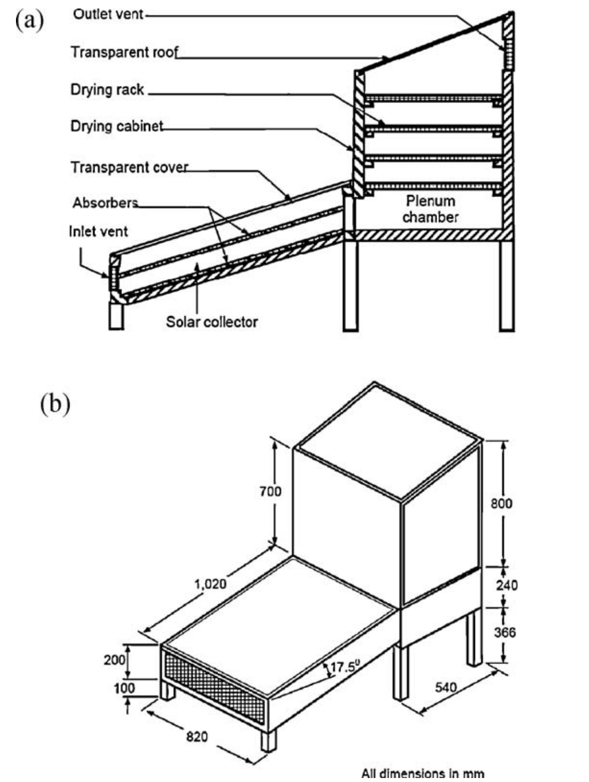


Fig. 11. A mixed-mode solar dryer: (a) sectional view and (b) isometric drawing [21].

Simate [22] designed, constructed and tested two different types of natural convection solar dryers (Fig. 12). They reported that, in both configurations, the dryer width is the same as the collector width. Airflow in the dryer is driven by buoyancy pressure created in: (i) the single covered collector with flow over the absorber, (ii) the space below the grain bed, (iii) the grain bed and (iv) the space above the grain bed. For the mixed-mode, the

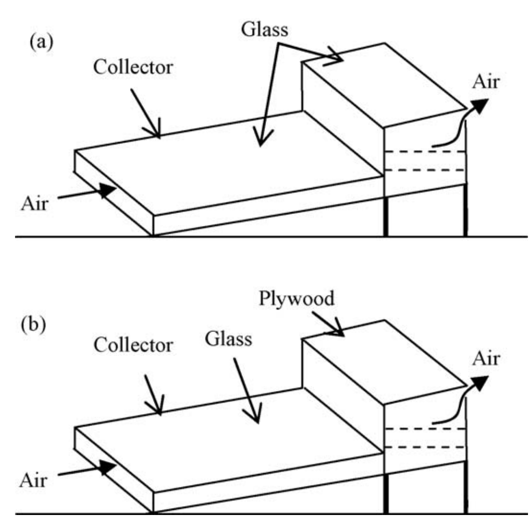


Fig. 12. Natural convection solar dryers: (a) mixed-mode and (b) indirect-mode [22].

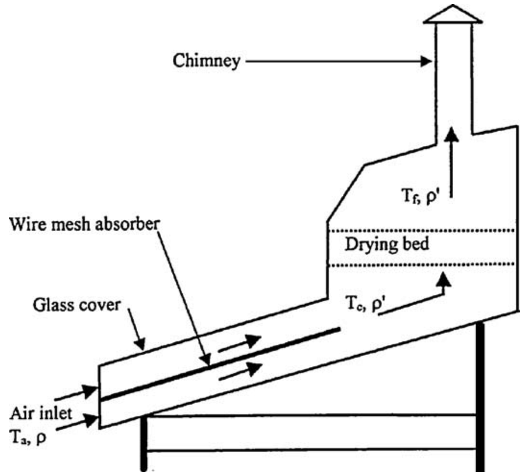


Fig. 13. Cross-section of solar dryer showing collector, drying chamber and chimney [23].

drying chamber cover is transparent whereas for the indirect-mode it is opaque. He calculated shown that optimization gave a shorter collector length for the mixed-mode solar dryer (1.8 m) than for the indirect-mode dryer (3.34 m) of the same capacity (90 kg). The drying cost of the mixed-mode dryer is 12.76 US$/ tonnes and is about 26% lower than that of the indirect-mode; the quantity of dry grain obtained from the mixed-mode for the whole year is about 2.81 tonnes and is less than that from the indirect-mode by 15%.

Madhlopa et al. [23] developed a solar dryer which had composite absorber systems on the principles of psychrometry (Fig. 13). The dryer consists of a flat plate collector, wire mesh absorber, glass cover, chimney and drying chamber. The drying chamber frames and both the collector were constructed from wooden sheets painted pink. Both the collector was integrated to a drying chamber for food dehydration. Results showed that the temperature rise of drying air was up to 40 °C during noon hours. The thermal efficiency of flat plate collector and wire mesh absorber were approximately 21% and 17% respectively at flow rate 0.0083 kg s^{-1}.

Forson et al. [24] designed a mixed-mode natural convection solar dryer (Fig. 14). The dryer consists essentially of an air heater, a drying chamber and a chimney. They proposed a methodology combining principles/concepts and rules of thumb, that enable the design of a properly engineered mixed-mode natural convection solar crop dryer. The resulting empirical model requires the crop physical properties and the location ambient conditions as input data.

Pangavhane et al. [25] designed and developed a multipurpose natural convection solar dryer consisting of a solar air heater and drying chamber. The solar air heater consists of an absorber (painted matte black) with fins, glass cover, insulation and frame. The air duct beneath the absorber was made from an aluminium sheet through which air was passed. The U-shaped corrugations (11 in number) were placed in the absorber plate parallel to the direction of airflow. Aluminium fins (a matrix foil 0.15 mm thick) were fitted to the back of the absorber. At the lower end of the collector (air inlet), shutter Plates 4 mm thick and 0.08 m × 0.4 m in size, were also provided to stop the air flowing during the night. At the upper end (air outlet) of the collector, a flange portion was provided to connect the flexible connector with nuts and bolts. The air duct was made leak-proof with a good quality sealing material. The entire unit was placed in a rectangular box made from a galvanized iron sheet 0.9 mm thick. The gap between the bottom of the air duct and the box was filled with glass wool insulation. This

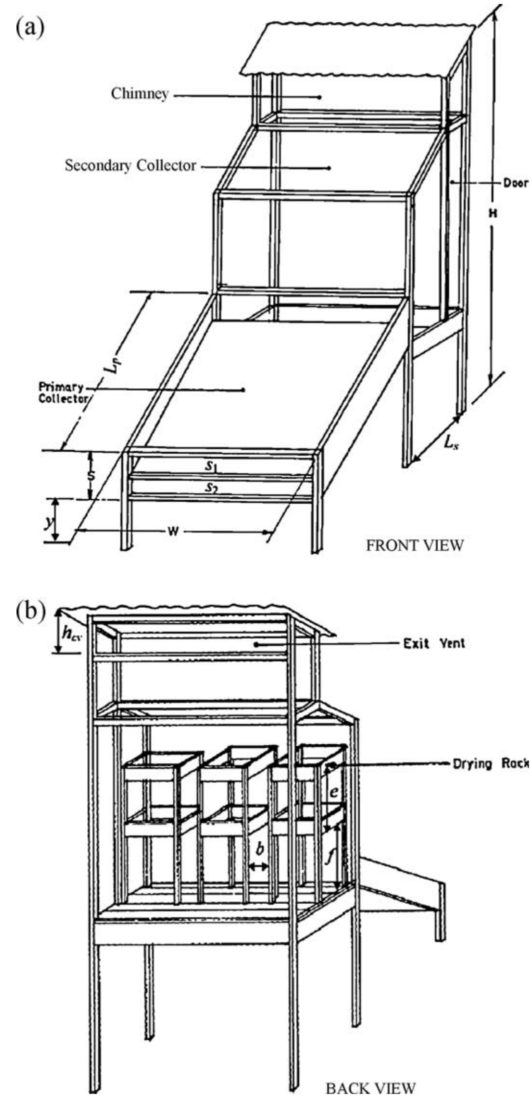


Fig. 14. Schematic view of mixed-mode passive dryer: (a) front view and (b) back view [24].

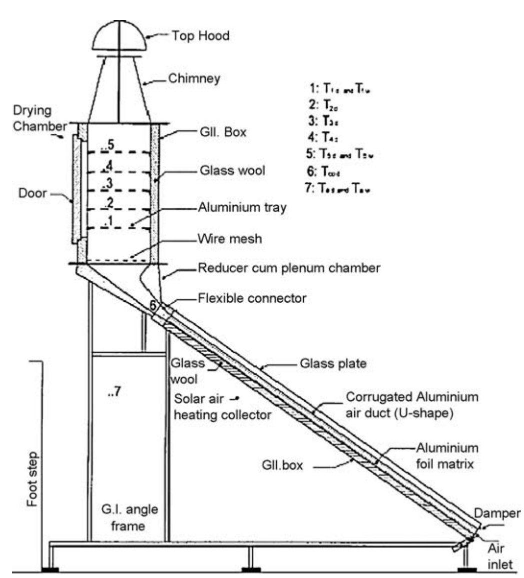


Fig. 15. A multipurpose natural convection solar dryer [25].

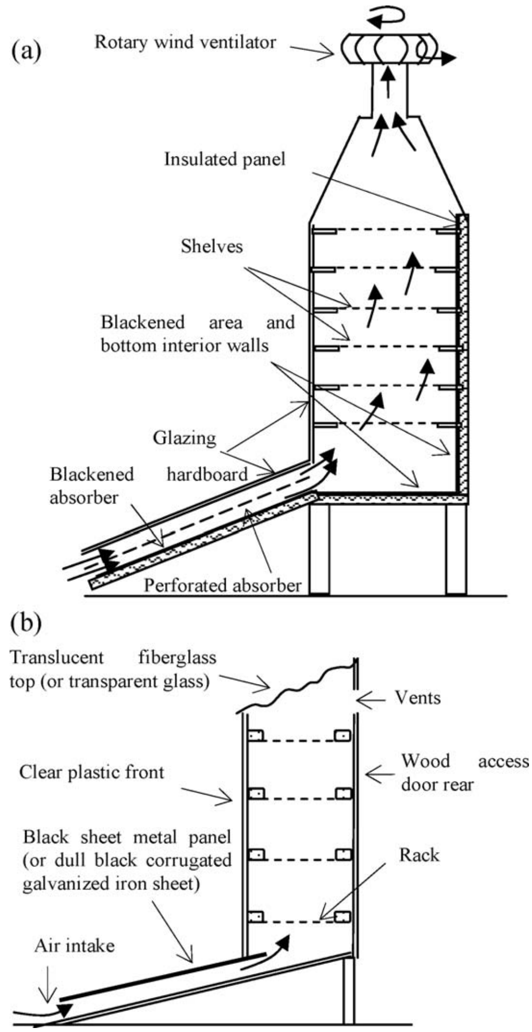


Fig. 16. A mixed-mode passive dryers: (a) multipurpose wind-ventilated natural convection solar dryer [4] and (b) a multi-stacked mixed-mode natural convection solar dryers [54].

system can be used for drying various agricultural products like fruits and vegetables. In this study, grapes were successfully dried in this solar dryer (Fig. 15).

A mixed-mode wind-ventilated natural convection solar dryer has been reported by Ekechukwe and Norton [4] in their review. The drying system (Fig. 16a) consists essentially of a solar air heater integrated to the drying chamber at the base, and a rotary wind ventilator at the top of the dryer chimney. The warm air outlet of the air heater is connected to the base of drying chamber. To reduce the heat losses, the north-facing wall and bottom horizontal panel are blackened. Addition drying also is achieved from direct solar radiation falling over the product through transparent side, front, and top panels. The rotary wind ventilator was built from moving corrugated vane rotor.

A typical design of the solar rice dryer is shown in (Fig. 17) has been reported also by Ekechukwe and Norton [4]. "This dryer consists of a solar air heater, a cabinet for the rice bed and a chimney which provides a tall column of warm air to increase buoyancy. The air heater's absorber consists of a thick layer of burnt rice husks covered by a clear plastic sheet on an inclined bamboo framework. The drying chamber is a shallow wooden box with a base made of bamboo mat with a fairly open structure to allow far and easy flow of the drying air. It is covered with a nylon netting to prevent the rice grains from falling through. A clear plastic sheet covering the rice bed allows the direct heating of the rice (by direct absorption of solar radiation) while protecting it against rain. The chimney consists of a bamboo framework clad with dark plastic sheet (which absorbs solar radiation, thus keeping the chimney inside warm)".

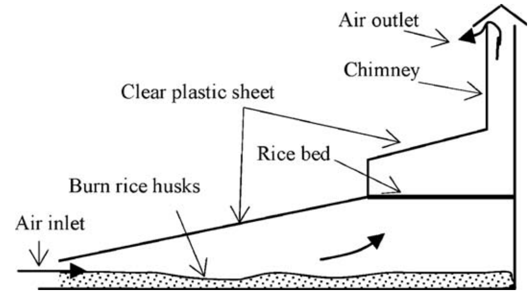


Fig. 17. Mixed-mode natural convection solar dryers (chimney-type) [4].

Singh et al. [26] developed a natural convection solar dryer. The dryer has a multi-shelf-design with intermediate heating, passive, integral, direct/indirect and portable solar dryer. It has four main components, multi-tray rack, movable glazing, shading plate and trays. The multi-rack is inclined depending upon the latitude of the location. The movable glazing consists of a movable frame and a UV stabilized plastics sheet. It is fixed on the movable frame. The dryer is low cost to make it economically viable. It can be used in cottage industries in remote places (Fig. 18).

Sharma et al. [27] investigated a multistacked natural convection solar dryer (Fig. 19). It is a simple solar dryer housed in a single cubic wooden box. The box has been divided into two halves. The

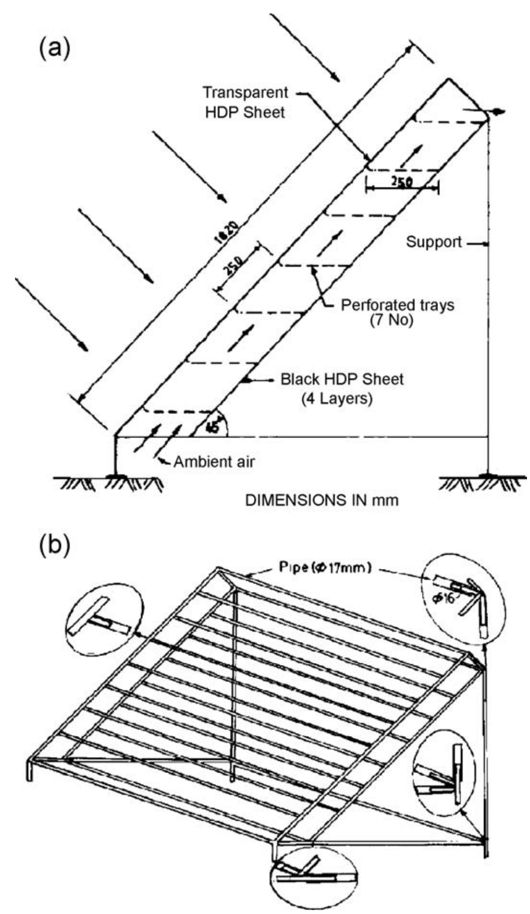


Fig. 18. Multi-shelf portable solar dryer: (a) side view of dryer and (b) detail of multiple-tray rack [26].

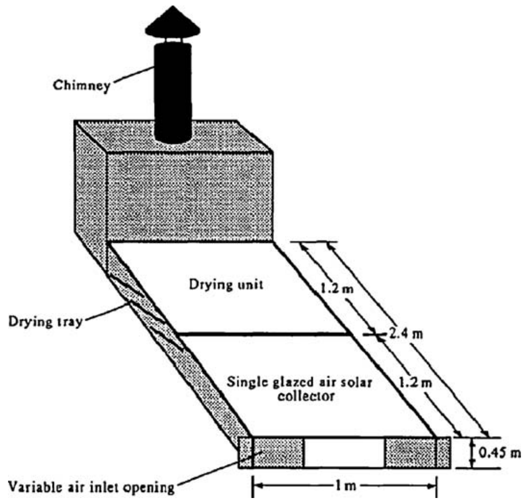


Fig. 19. General overview of solar dryer [27].

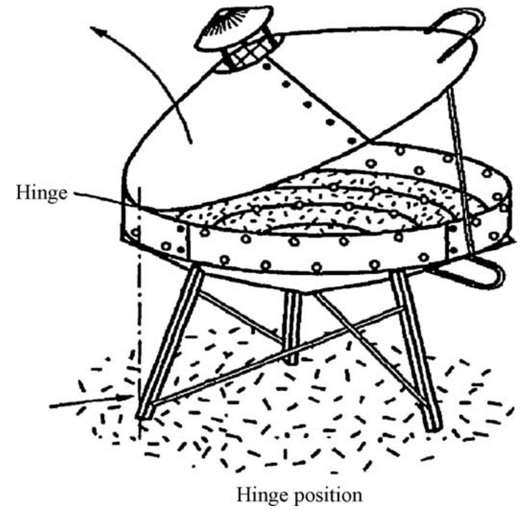


Fig. 21. Illustration of the shell dryer [30].

first half is a singleglazed solar air collector, whereas the drying unit is in the second half of the complete unit. A glazed solar air heater located at the base of the drying chamber provides supplementary heat. Preheated air in the solar collector rises through the second half of the system. A chimney is provided at the top of the drying unit. The hot air dehydrates the product and gets exhausted through the chimney. The dried product is placed on the moveable trays kept on the metallic frames. The system can be operated both in natural as well as in forced convection mode.

Goyal and Tiwari [28,29] developed and analyzed a model using both a reverse flat-plate absorber as the heating medium and a cabinet dryer as the drying chamber. The whole unit is termed a reverse absorber cabinet dryer (RACD) is shown in Fig. 20. The absorber plate is horizontal and downward facing. A cylindrical reflector is placed under it to introduce solar radiation from below. The area of the aperture is the same as that of the absorber plate. The cabinet dryer is mounted on top of the absorber maintaining a gap of 0.03 m for air to flow above the absorber. The incoming air will be heated and enters the dryer from the bottom. The dryer is not insulated from the bottom but it does not allow insulation from the top. The bottom area of the dryer is equal to that of the absorber plate area. The inclination of the glass cover is taken as 45° from horizontal to receive maximum radiation. The thermal performance of the new proposed dryer is analyzed by solving the various energy balance equations using the finite difference technique. A mathematical expression is proposed for RACD and results are compared with those for a normal cabinet dryer.

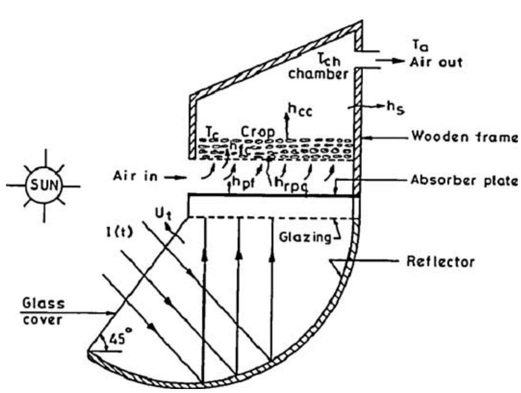


Fig. 20. Reverse absorber cabinet dryer [28].

Fig. 21 shows indirect solar drying systems, namely the shell dryer, integral natural convection solar dryers. The dryer consists of an upper cone, a cylindrical dehydration chamber and a bottom cone. The upper cone is truncated at the top and is topped by a cap that can slide to allow adjustment of the airflow section. The cylindrical dehydration chamber can hold two trays in which the product to be dried is loaded. The bottom cone is identical to the upper one but is positioned in the opposite orientation and drilled with a number of regularly distributed holes. The absorber is unglazed, resulting in high heat losses to the ambient. So, most of the solar energy gain by the conical absorber is used to make the airflow through the product, and drying is mainly by aeration. The only advantage is that the product is dried under shade [30].

As shown in Fig. 22, the glass roof solar dryer is basically used to greenhouse system. The drying unit consists of two parallel rows of drying platform made of galvanized iron mesh laid over wooden beams. The dryer aligned lengthwise in the north-south axis. Air passes through the wire mesh, gets heated and picks up the moisture from the products spread over it. To facilitate the convection and ventilation, the trays and inner side of dryer were painted black, and openings are provided on the eastern and western walls, above and below the level of platform containing the product as reported by [4].

Another greenhouse dryer with natural circulation is shown in Fig. 23. Greenhouse dryers are more sophisticated version of tunnel dryers. The dryer consists of a framework with plastic film of semi-transparent polyethylene on the side facing sun and at the ends. Solar tunnel dryer was oriented in an east-west direction to make the solar radiation incident more efficient. This allows a lower initial cost. The main purpose of the dryers to provide protection from dust, dirt, rain, wind or prevent insects and bird [31].

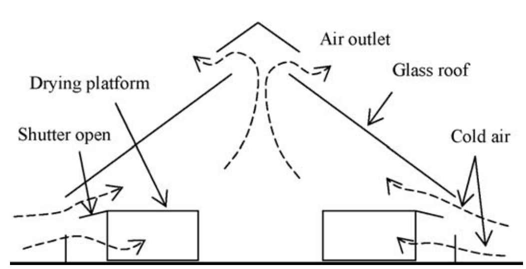


Fig. 22. Natural circulation glass roof solar dyer [4].

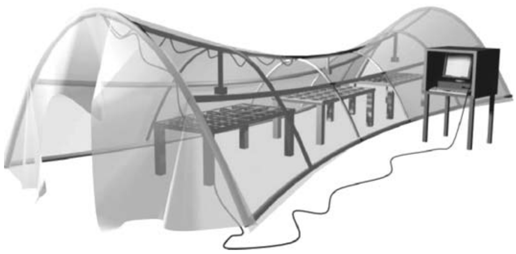


Fig. 23. Annual circulation greenhouse tunnel dryer [31].

N'Jai [32] tested three different types of natural convection solar dryers for drying fermented fish in the Gambia (Fig. 24). He reported that all the dryers have structure frames made of rhun palm sticks which are low cost and available locally and covered with clear polyethylene material. Solar tent dryer consists of the side vents are 0.5 m high and 6 m long, the top vents are triangular in shape, the front one has an area of 0.7 m^2 and the back vent is somewhat smaller. House shaped solar dryer consists of the side vents are 1 m wide and 6 m long, the top vents are area of 0.5 m^2 each (front and back). In both dryers, inside the dryer are two rectangular racks stretching along the sides of the dryer. There is a door at one end of the dryer. Solar dome dryer consists of six metal hoops shaped as arches form the frame, two doors back and frond, vents along the bottom of the side walls and along the top at the centre of the arch. Inside the dome are vertical and horizontal beams: the latter allow for the fish to be hung on hooks while drying.

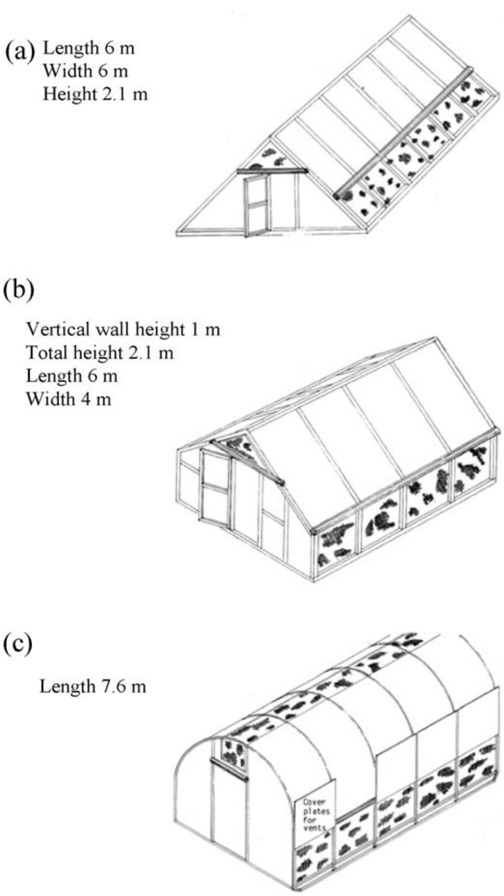


Fig. 24. A natural circulation greenhouse dryer: (a) solar tent dryer, (b) solar house dryer and (c) solar dome dryer with handing fish [32].

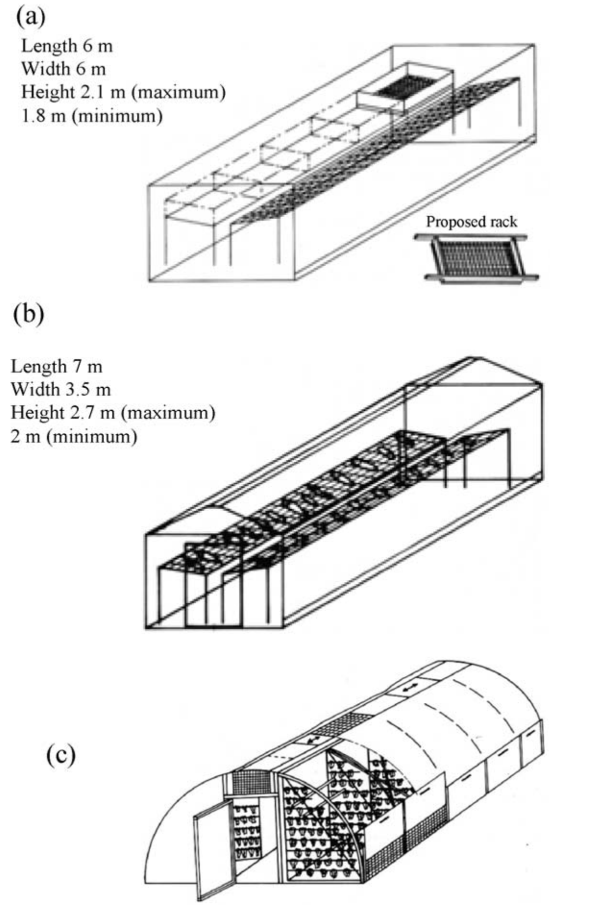


Fig. 25. A natural circulation greenhouse dryer: (a) drying racks in the Brace-type solar dryer, (b) solar house dryer and (c) solar dome dryer with handing fish [33].

Diouf [33] reported three different types of dried fish using natural convection solar dryers (Fig. 25). The frame is made from metal for the dome dryer and from wood for the other two. All the dryers have covered with clear polyethylene material. The vents at the base run the length of the dryer and, like those on the top, are fitted with fine-mesh plastic netting to prevent flies from entering the dryer. A door allows access by the processors. The supports used in rack fish drying operations cover the entire floor except for the part used as a walkway by the processors. These racks have an openwork structure to allow the drying air to pass through. The product to be dried is distributed uniformly along the rack, with small regular spaces left so that it can be turned over periodically, than the degree of drying can be controlled.

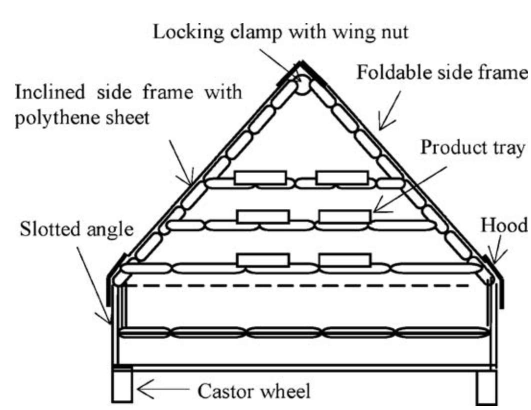


Fig. 26. Foldable solar crop dryer [34].

Fig. 26 shows a foldable solar crop dryer that operates on the same principle of the glass roof dryer. This dryer is made from aluminium sheet as sidewall material and painted black from the outside. The inside temperature of the dryer was twice that of the ambient at noon. The main drawback of this dryer was that an increase in outside wind velocity may reduce the inside temperature because the heating takes place on the outer surface of the dryer [34].

Two different types of natural circulation greenhouse (Fig. 27) crop dryers were designed, constructed and tested by Koyuncu [35]. Each dryer mainly consists of a framework constructed from black coated metal bars, corrosion resistant plastic mesh, black coated solar radiation absorber surface, styrfor insulation, polyethylene cover sheet, product door, air inlet and outlet channels and chimney. The frameworks of the dryers were clad with clear polyethylene sheet on the all sides. The cladding at rear side was arranged to allow put the moist products into the drying chamber or get dried product from there. The clear plastic cladding at the bottom edge of the front side and rear side was also arranged to allow air to flow into the chamber, while the rectangular stream at the top of the end served as the exit for the moist exhaust air. The results of the study show that the greenhouse solar dryers increase the ambient air temperature 5–9 °C, and these dryers are 2–5 times more efficient than plastic mesh platform type open sun dryer. The dryers with a drying air outlet chimney give better value of air mass flow by increasing the air velocity. The black-painted solar absorber surfaces raise the efficiencies of the dryers. The general conclusion is that these greenhouse solar dryers are 2–5 times more efficient than open sun dryers and they are of much superior quality as compared to open sun drying. It is, therefore, concluded that these dryers can be used successfully for drying a variety of agricultural products, especially fruits and vegetables.

Ekechukwu and Norton [36–38] designed and developed natural convection solar dryers which are suitable for the drying of most crops. The design is a simplified design of the typical greenhouse type natural convection solar dryer (Fig. 28). It consists of a cylindrical polyethylene-clad vertical chamber, supported structurally by a steel framework and draped internally with a selectively absorbing surface. They reported that performance of the dryer studied was dependent largely on the variations in insolation, ambient temperature and relative humidity. The results obtained from experimental solar chimneys, if designed properly could maintain chimney air temperatures consistently above the ambient temperature which would enhance the desired buoyancy-induced airflow through the chimney and drying rate. Linear correlations have been obtained between the drying rate measured experimentally and a group of ambient and crop parameters. The underlying concept of these correlations may form the basis for the development of solar dryer design charts which are currently not available.

Ahmad [39] has been paid to build a simple solar air heater from cheap plastic wrapping film with air bubbles, for use in drying operations on a farm (Fig. 29). The model used was a single-sheet cylindrical collector and, after it had gained some heat, another layer of the plastic wrapping film with air bubbles was added in a later stage to decrease convection heat losses to the surroundings. Each cylindrical collector was 5 m long and 0.36 m in diameter, with a black interior band covering the lower part of the collector (30% of the surface area). The inlet direction of the collector was always towards the wind in order to achieve maximum airflow

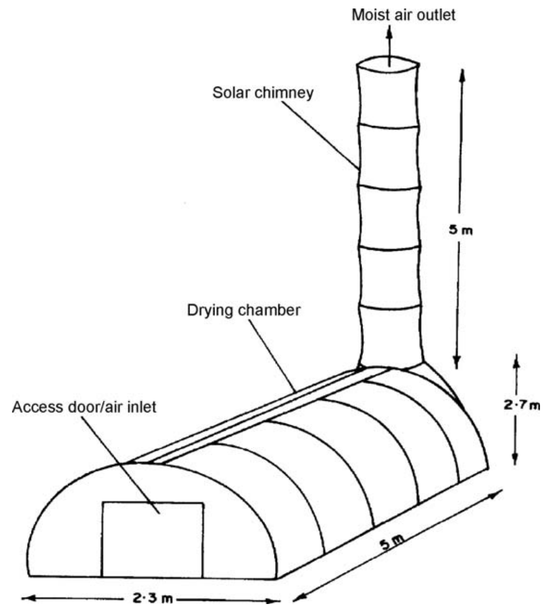


Fig. 28. Schematic illustration of the experimental natural circulation solar dryer [38].

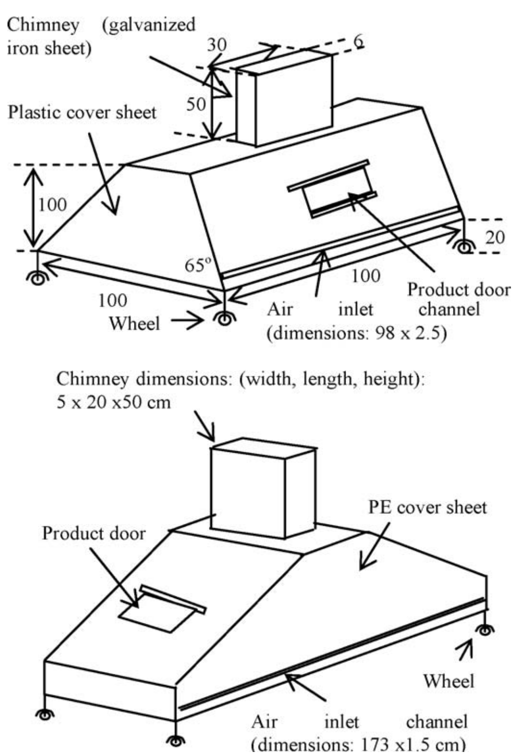


Fig. 27. A simple greenhouse dryers [35].

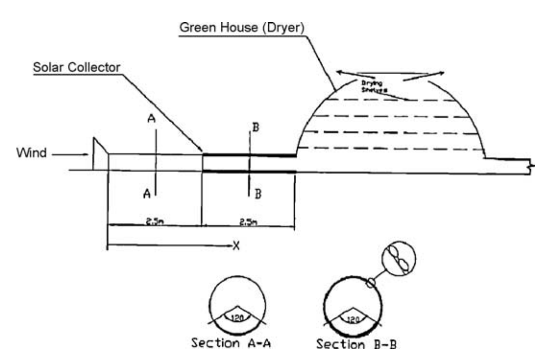


Fig. 29. Schematic diagram of the solar drying system [39].

inside the collector. Although the method used is simple, a considerable gain in the temperature of the airflow was obtained: a temperature difference of around 10 °C was measured. He reported that use of the transparent insulation (bubble film) results in a considerable improvement of the collector performance compared with the single-sheet collector. Therefore it is recommended to use this transparent insulation to cover all of the collector or at least the lower part of it, rather than the two stages used in this work. The choice of this collector is determined by market availability, its ease of construction and maintenance, and its ability to give a good level of efficiency.

3.2. Forced convection dryer (active dryers)

Direct mode forced convection dryers essentially consist of a blower to force the air through the product, a chamber, and covered with a transparent sheet. Indirect-mode forced dryers essentially consists of an air heater, drying chamber, and a blower/fan to duct the heated air to the drying chamber, illustrated in Fig. 30.

Al-Juamily et al. [41] constructed and tested an indirect-mode forced dryer (Fig. 31) for drying fruit and vegetable in Iraq. The solar drying consisted of a solar collector, a blower, and a solar drying cabinet. Two identical air solar collectors having V-groove absorption plates of two air passes, a single glass cover was used. The total area of the collectors is 2.4 m^2. The dimensions of the drying cabinet are 1 m × 0.33 m × 2 m (width, depth, and height). The cabinet is divided into six divisions separated by five shelves. The distance between the shelves is 0.3 m except the upper one, which is 0.5 m from the roof. Each shelf is 0.95 m × 0.3 m and is made of metallic mesh. The drying chamber walls are made of aluminum plate except the southern side, which was fixed with glass plate having the dimensions 1 m × 2 m × 0.002 m. Two types of fruit and one type of vegetables were dried during the present work. These were grapes, apricots, and beans. The moisture content of apricot has been reduced from 80% to 13% within one day and a half of drying. Moreover, the moisture content of grapes has been reduced from 80% to 18% in two and a half days of drying. Finally the beans has been reduced from 65% to 18% in 1 day only. They concluded that air temperature is the most effective factor on drying rate. The effect variation of speed of air inside the drying cabinet is small and can be neglected. They also concluded that the relative humidity of air exit from the cabinet was small between (25 and 30%) and therefore there is no need for high velocity air inside the cabinet.

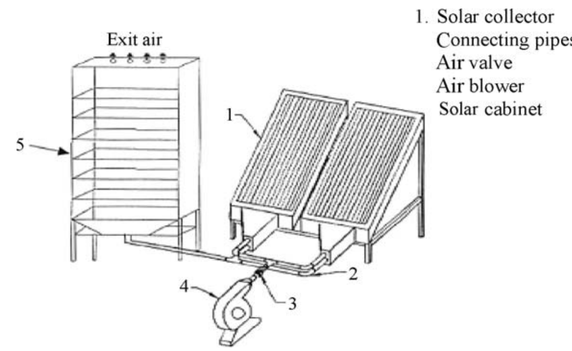


Fig. 31. Illustrate of indirect-mode forced dryers [41].

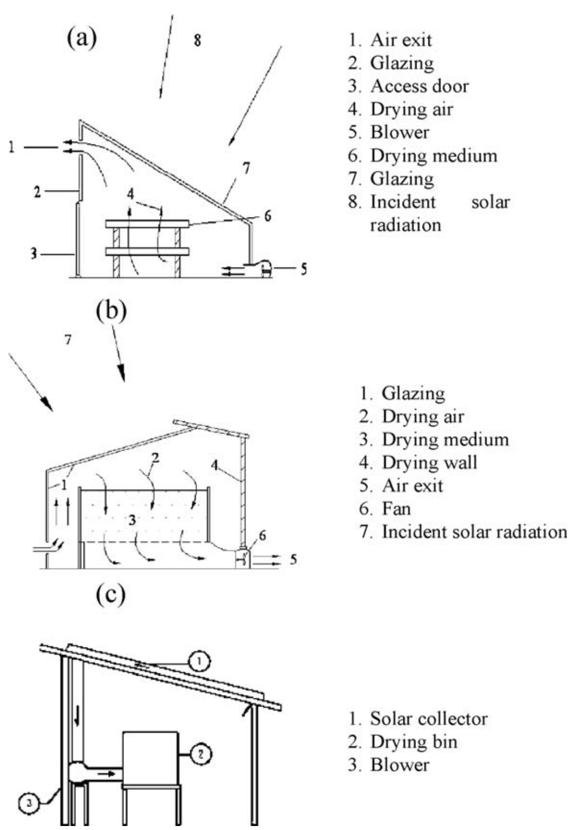


Fig. 30. Illustrate of forced circulation: (a) blower at inlet of collector [40], (b) fan at outlet of drying chamber [40] and (c) blower between collector and drying chamber [54].

Solar drying system using V-groove solar collector is also developed and tested by Kadam and Samuel [42] for drying cauliflower. Its main components were galvanized iron sheet with black paint, transparent glass over it and a closed duct. The study was conducted to determine the thermal efficiency of the forced convective solar collector for drying cauliflower to obtain good quality dehydrated product. Thermal efficiency of the solar heat collector directly depends on solar radiation and humidity in the air.

Karim and Hawlader [43] determined that the V-groove collector was the most efficient collector and the flat-plate collector the least efficient. It results showed that V-groove collector has 7–12% higher efficiency than flat-plate collectors. Optimum conditions of three collectors were cited to perform up to approximately 70% thermally efficient at 0.031 kg/m^2s could be attained with the V-groove. The double pass operation of the collector improved the efficiency of all tree collectors. The efficiency of all the air collectors is a strong function of airflow rate. As flow rate of about 0.035 kg/m^2 s is considered optimal for solar drying of agricultural produce.

El-Beltagy et al. [44] developed a mathematical model of a thin layer drying for strawberry using an indirect forced convection solar dryer (Fig. 32). The dryer consisted of a drying chamber, and a

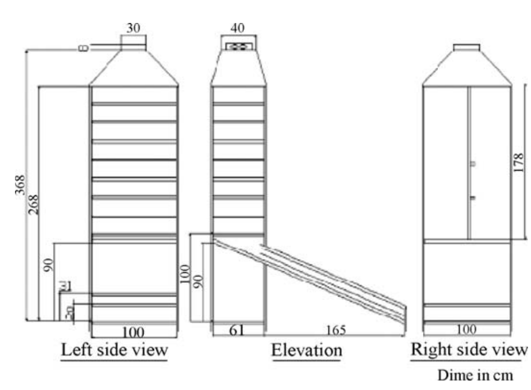


Fig. 32. Experimental forced indirect solar dryer [44].

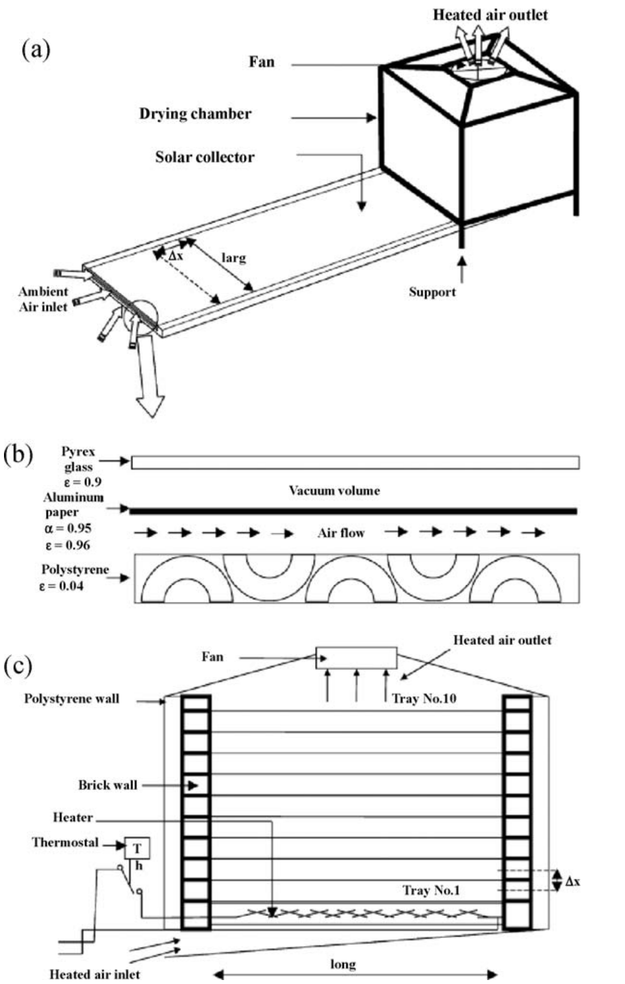


Fig. 33. (a) Diagram of solar batch dryer, (b) diagram of the collector and (c) internal diagram of the dryer chamber [45].

solar collector with W-corrugated black aluminium sheet to absorb the maximum possible of solar radiation. Heat dissipation by convection was minimized by placing a flat transparent glass cover 4 mm thick on top the corrugated sheet. The solar collector was tilted at an angle of 20° from the horizontal plane. Ambient air was drawn in by a fan and heated up in the solar collector.

Bennamoun and Belhamri [45] studied a simple efficient and inexpensive solar batch dryer for agriculture products (Fig. 33). The collector surface and the temperature of the heated air essentially affect solar batch drying. Their increase considerably reduces

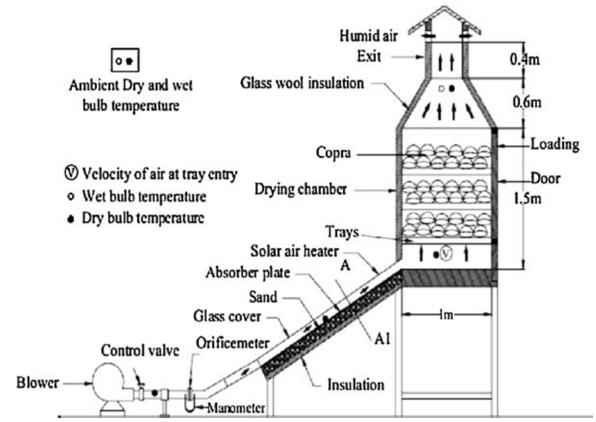


Fig. 35. Illustrate of indirect-mode forced dryers [47].

drying time. The influence of the dimension and the total mass of the dried product is less important. Using a heater has shown good improvement in the obtained results. It allows using the dryer in unfavorable climatic conditions and reaching in many studied cases the purposed moisture. Its use can present a rapid investment return. Using a solar batch dryer with 3 m^2 collector surface and a heater at 50 °C allows drying of about 250 kg per day.

Vlachos et al. [46] designed and tested a novel low cost solar-assisted indirect dryer equipped with a solar collector, a heat storage cabinet and solar chimney (Fig. 34). The design is based on energy balances and on an hourly averaged radiation data reduction procedure for tilted surface. The dryer is easy to construct and operate and can be implemented at low cost. Considering the different weather conditions tested (sunny, cloudy or rainy), the drying process reached full completion in all tests at a reasonable rate of dehydration. Experimentation over the night, without the use of the centrifugal fan, confirmed the system's good performance regarding the usefulness of the heat storage cabinet since the products' water content continued to decrease although at a lower rate. Fairly promising results were obtained regarding the solar dryer's efficiency as reported by [46]. The latter can be improved by properly adjusting the flow rate and temperature of the air entering the drying chamber. With regard to drying uniformity throughout the drying chamber special attention should be given to products placed at the lower drawer just above the entry points of the two flexible air ducts where excessively faster drying occurs. Periodic agitation of the solids in

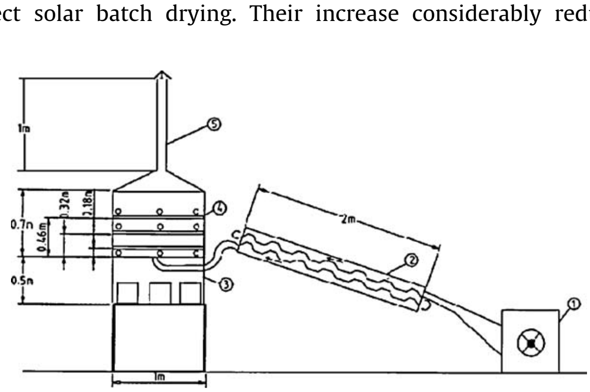


Fig. 34. An outlay of the solar dryer (1. centrifugal fan, 2. solar collector, 3. storage cabinet, 4. drying chamber, 5. solar chimney). The two corrugated sheets in the solar collector with the characteristic "reverse Z" air flow path as well as the relative position of the three drawers in drying chamber are also shown [46].

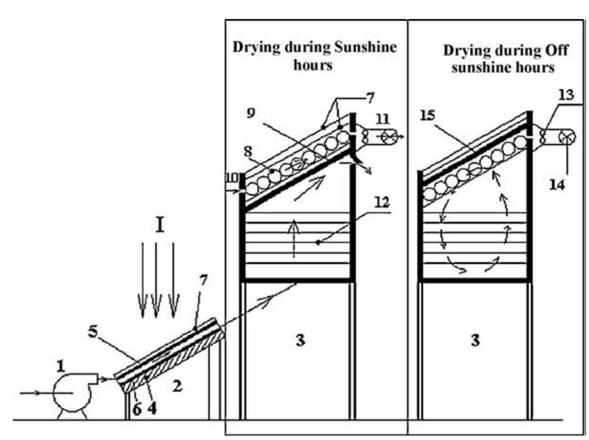


Fig. 36. Schematic of the desiccant integrated solar dryer (1. blower, 2. flat-plate solar air collector, 3. drying chamber, 4. insulation, 5. absorber plate, 6. bottom plate, 7. transparent cover, 8. desiccant bed, 9. plywood, 10. air inlet, 11. duct for air exit, 12. drying trays, 13. reversible fan, 14. valve, 15. plywood [48].

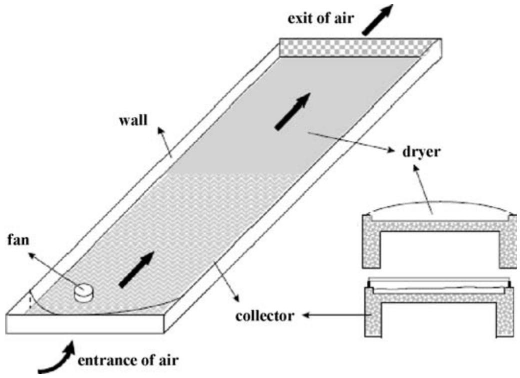


Fig. 37. A sketch of Hohenheim tunnel type installation of drying [49].

the lower drawer, exchange of drawer's position or a new design of the air exit section from the ducts may alleviate this problem.

Mohanraj and Chandrasekar [47] was design, fabricated and tested an indirect-mode forced dryer (Fig. 35) for the drying copra. It consists of a solar collector, a blower, and a solar drying cabinet.

Shanmugam and Natarajan [48] designed and fabricated an indirect forced convection with desiccant integrated solar dryer (Fig. 36). The main parts are: a flat-plate solar air collector, a drying chamber, desiccant bed and a centrifugal blower. The system consists of a flat-plate solar air collector, drying chamber and a desiccant unit. Drying experiments were conducted with and without the integration of desiccant unit. The desiccant unit was designed to hold 75 kg of $CaCl_2$-based solid desiccant consisting of 60% bentonite, 10% calcium chloride, 20% vermiculite and 10% cement. The effect of reflective mirror on the drying potential of desiccant unit was also investigated. With the inclusion of reflective mirror, the drying potential of the desiccant material is increased by 20% and the drying time is reduced. The drying efficiency of the system varies between 43% and 55% and the pick-up efficiency varies between 20% and 60%, respectively. Approximately in all the drying experiments 60% of moisture is removed by air heated using solar energy and the remainder by the desiccant. The inclusion of reflective mirror on the desiccant bed makes faster regeneration of the desiccant material.

Hodali and Bougard [49] designed and integrated an adsorption unit silica gel for a crops solar drying installation. The drying installation consists of a forced convection direct dryer connected to a solar collector as shown by schematic diagram in Fig. 37. The daily sorption cycle of the desiccant unit is first investigated and a suitable coupling of the collector, the dryer and the adsorption unit has been selected. The coupling is numerically simulated and applied to the drying of apricots in Morocco under real climatic conditions. The integration of the adsorption unit allowed improving the quality of the dried product and permitted a cyclic operation of drying over 2 days by reducing the drying period from 52 to 44 h.

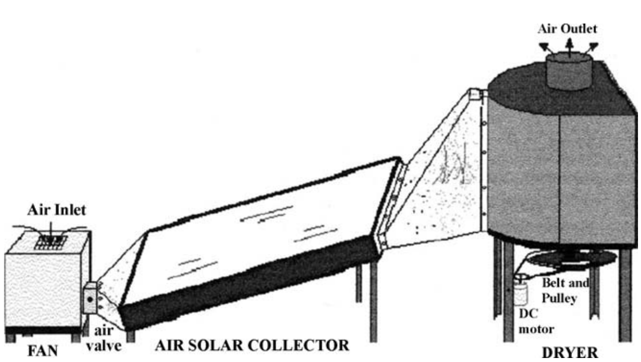


Fig. 38. Rotary column cylindrical drier [50].

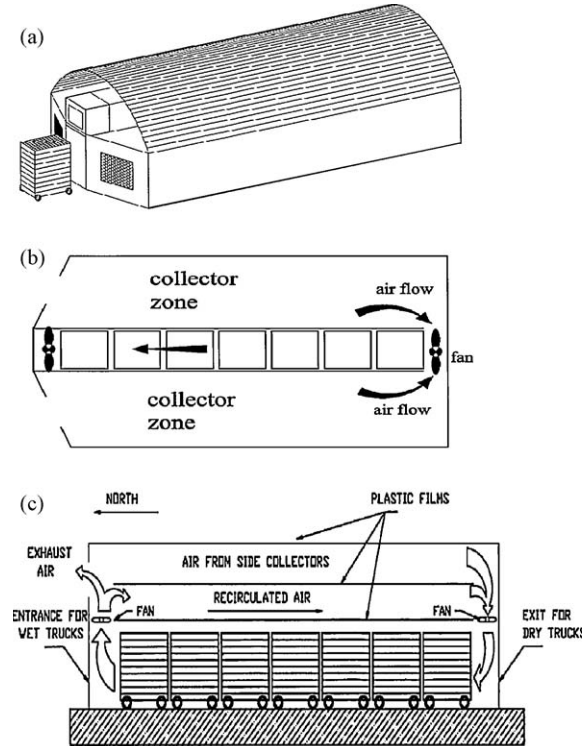


Fig. 39. Forced convection tunnel greenhouse dryer: (a) face view, (b) plant view and (c) operation scheme [51].

Sarsilmaz et al. [50] conducted experiments on drying of apricots in a newly developed rotary column cylindrical dryer (RCCD) equipped with a specially designed air solar collector to find optimum drying air rate and rotation aped of dryer, to maintain uniform and hygienic drying conditions and to reduce drying times. Fig. 38 shows the complete drying system. The systems are constituted of three parts: air blow region (fan), air heater region (solar collector) and drying region (rotary chamber). Drying operation is of prime importance which is applicable to almost all the agricultural products.

Condori et al. [51] built and tested a low cost design for a forced convection tunnel greenhouse drier (Fig. 39). Its main parts are: a plastic greenhouse cover containing a drying tunnel made with transparent plastic walls; a line of carts with several stacked trays containing the product and moved manually inside the tunnel and an electrical fan that moves the hot air from the greenhouse into the tunnel. The main advantages of this drier were: (a) an almost continuous production since some carts with dried product come

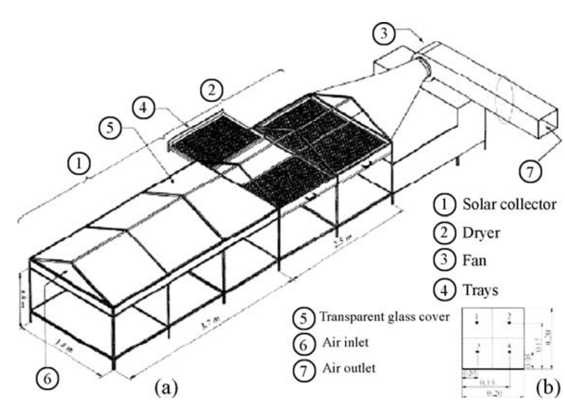


Fig. 40. (a) General view of solar tunnel drier and (b) positions of the velocity measurement [53].

out of the tunnel every day, while the same amount of fresh product was introduced by the other tunnel extreme; (b) lower labor cost since the product handling was partly mechanized; (c) a conventional heater can be easily installed to keep a constant production rate; (d) the energy consumption was lower than in other drier types; (e) the installation can be used as a greenhouse for small production when it is not used as a drier.

Condori and Saravia [52] studied analytical of the evaporation rate in two types of forced convection greenhouse driers, the single and the double chamber system. A performance parameter defined to compare both driers and its dependence on the operational variables is studied introducing the concept of the characteristic function. They reported that the simulation results show that a higher production rate can be obtained improving the use of the drying potentials. Particularly, the productivity of the double chamber greenhouse drier compared to the single chamber-type is increased by 87% for the same drier area. The necessary changes needed to implement the double chamber drier are simple and inexpensive reducing significantly the drying cost.

Usub et al. [53] studied an experimental analysis to investigate the performance of a mixed-mode type forced convection solar tunnel dryer (Fig. 40) which was used to dry silkworm pupae under tropical weather conditions of Mahasarakham, Thailand. The dryer consisted of a transparent glass covered flat-plate collector and a drying tunnel connected in series to supply hot air directly into the drying tunnel using a blower. The dryer was 6.2 m long and 1.8 m wide. The drying unit had a loading capacity of 30 kg of silkworm pupae. They reported that maximum drying and overall efficiencies were 30.14% and 19.68%, respectively, at the air flowrate of 0.30 kg/s. The economic analysis indicates that the payback period is 1.42 years.

Fig. 41 shows a forced convection solar banana dryer was investigated in Pitsanuloke province, Thailand. The unit comprised a drying cabinet covered by 12 m^2 of clear glass and 32 m^2 of flat-plate solar air heater. In operation, warm air was drawn by the solar collector and was blown through a heat exchanger before entering the drying cabinet where solar radiation was absorbed by the drying product.

3.3. Hybrid solar dryers

3.3.1. Solar drying system with thermal storage

Several workers have explored different technique for drying various agricultural products by considering the possible use of solar collector as sources of supplementary heat, and developed deep bed drying model to predict the performance [55–60]. Tiwari et al. [55,56] have experimentally evaluated a crop dryer cum water heater and crop dryer rockbed storage (Fig. 42). They reported energy balance equations for each component of the system have been used to predict the analytical results. On the basis of the analytical results, it is observed that the drying time is significantly reduced due to the increase in thermal energy on the collector by the reflector. The system can be used to provide hot water in case the drying system is not in operation. The water heater below the air heater systems will act as a storage material for drying the crop during off-sunshine hour.

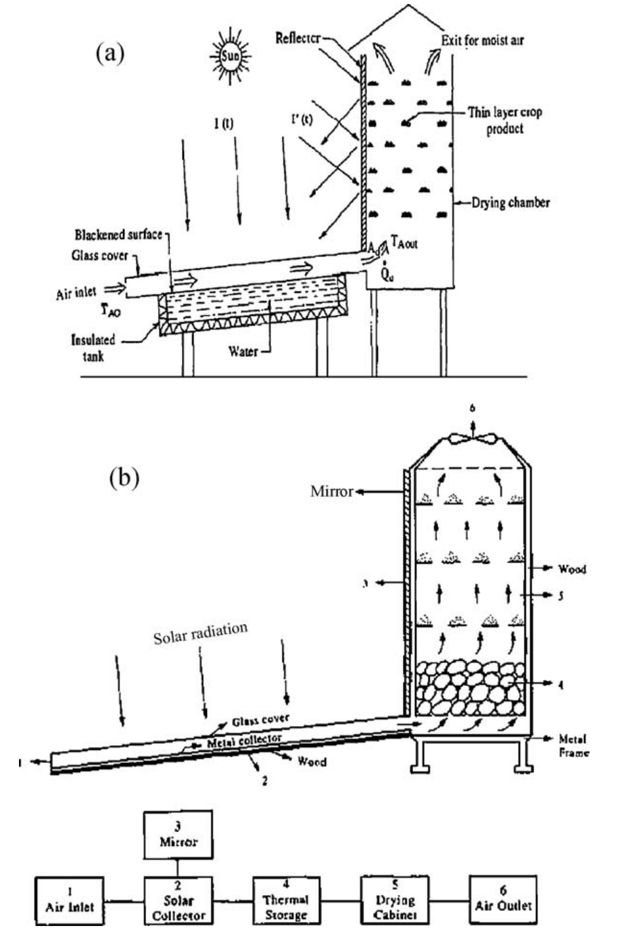


Fig. 42. Cross-sectional view of the crop dryer: (a) with cum water heater [55] and (b) with rock bed storage [56].

Comparative performance of coriander dryer coupled to solar air heater and solar air heater-cum rock bed storage was studied by Chauhan et al. [57]. They concluded that the average moisture content of the grains in the grain bed can be reduced from 28.2%

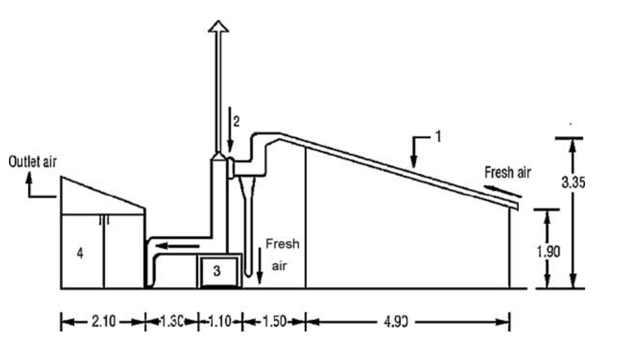


Fig. 41. Forced convection greenhouse solar dryer (1. solar collector, 2. blower, 3. burner stove, 4. greenhouse) [54].

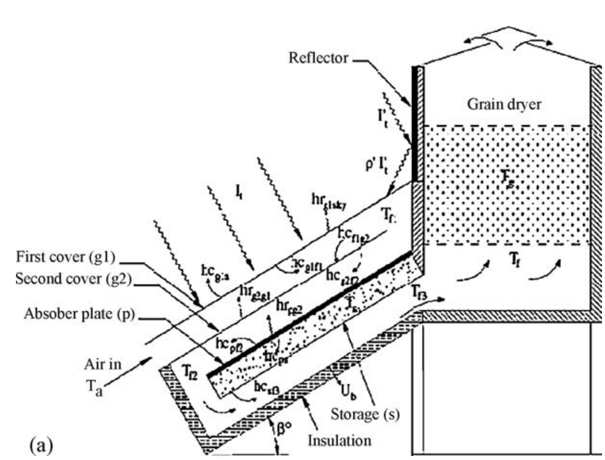


Fig. 43. Cross-sectional view of the crop dryer inclined multi-pass air heater with in-built thermal storage with reflector [58].

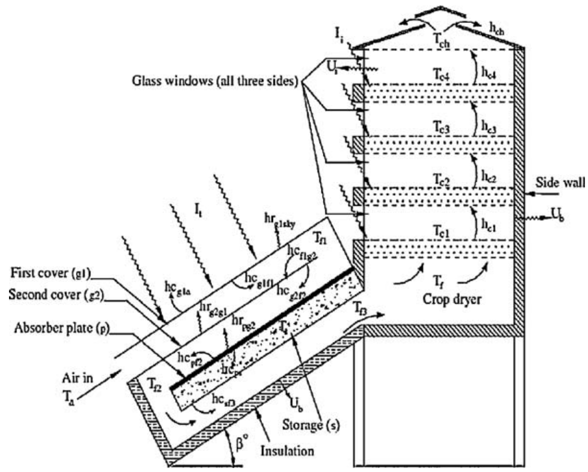


Fig. 44. Cross-sectional view of the crop dryer inclined multi-pass air heater with in-built thermal storage without reflector [59].

(db) to 11.4% (db) in 27 cumulative sunshine hours (i.e. 3 sunshine days) by using the solar air heater only, whereas by using the solar air heater during sunshine hours and the rockbed energy storage during off-sunshine hours the same amount of moisture can be evaporated in 31 cumulative hours (18 sunshine and 13 off-sunshine hours). During sunshine drying, the effect of grain bed depths on drying performance of coriander is observed to be remarkable, while the air mass velocity has no significant effect on the moisture content reduction rate. However, off-sunshine drying time can be reduced by 1 h for each increment of 50 kg/hm^2 in air mass velocity. Hence, the heat stored in the rockbed can be used effectively for heating the inlet (ambient) air for off-sunshine drying of agricultural products.

Jain [58,59] modeled the system performance of multi-tray crop drying using an inclined multi-pass solar air heater with in-built thermal storage (Figs. 43 and 44). The proposed mathematical model is useful for evaluating the thermal performance of a plat plate solar air heater for the crop drying in multiple trays. It is also useful for predicting the moisture content, crop temperature and drying rate in the different drying trays. The results showed that the grain temperature increase with the increase of collector length, breadth and tilt angle up to typical value of these parameters. The thermal energy storage also affect during the off-sunshine hours is very pertinent for crop drying applications.

Ekechukwe and Norton [4] reported in thier review that Ayensu and Aseiedu-Bondizie [60] designed a mixed-mode natural convection solar dryer (chimney-type dyer), as shown in Fig. 45.

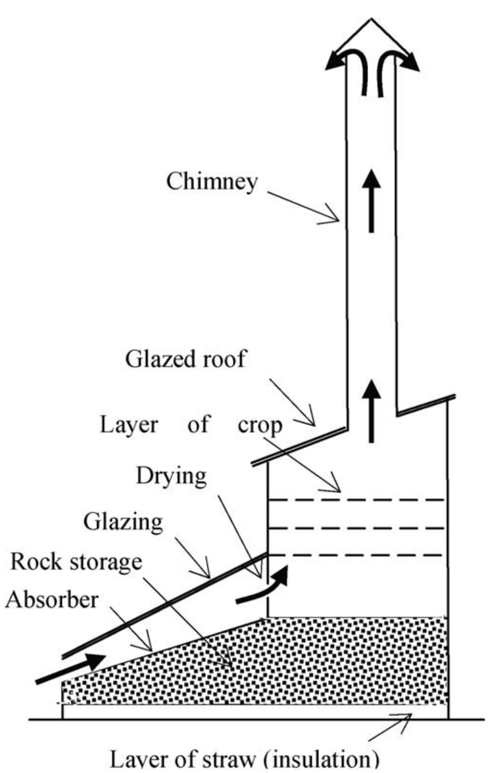


Fig. 45. Cross-section view of the indirect type natural convection solar dryer with storage [4,60].

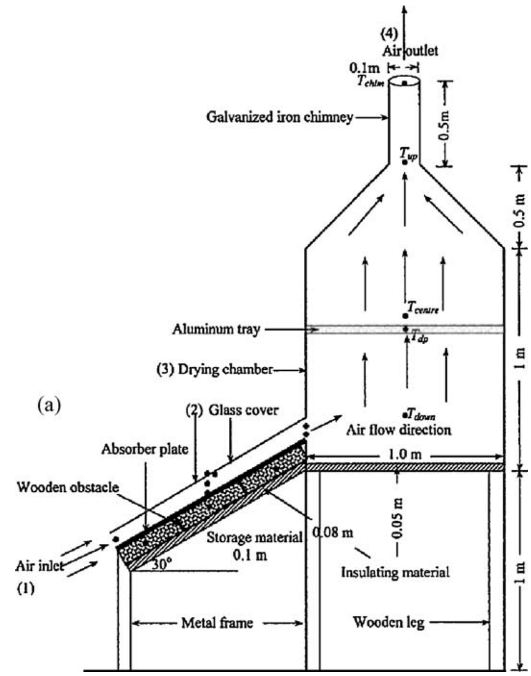


Fig. 46. Cross-section view of the indirect type natural convection solar dryer with storage [7].

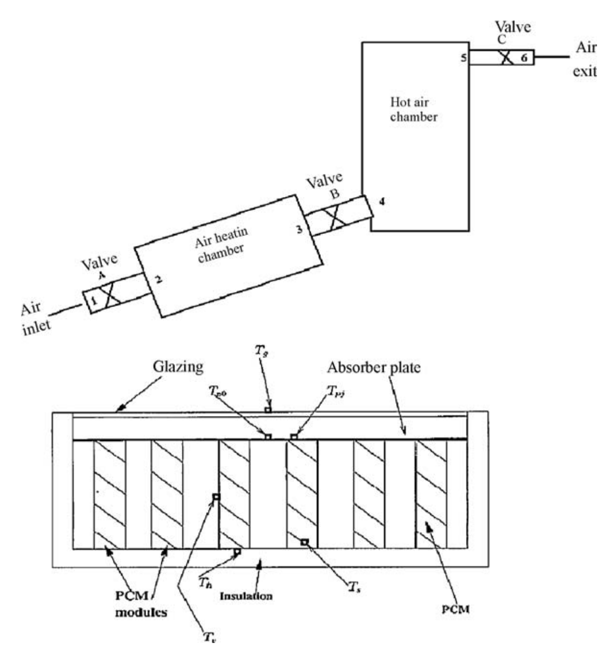


Fig. 47. (a) Schematic view of a natural convection solar dryer and (b) cross-sectional view of the collector assembly [61].

It consists a single layer of glass was used as a glazing, drying chamber, chimney and an air collector-cum-rock bed storage (granite) insulated from the base ground by a thick layer of straw. The drying chamber made of plywood sides with a glazed top, held 3 layers of wire mesh within it. The chimney consists of 30 cm diameter, 1.9 m height above the chamber and was made from matt black-painted galvanized iron sheets fitted with a metal cap at the top to keep out rain.

El-Sebali et al. [7] designed an indirect type natural convection solar dyer (Fig. 46). It consists of a flat-plate solar air collector, drying chamber, storage material and chimney. Sand was used as the thermal storage material. The drying parameters such as drying temperature, ambient temperature, relative humidity, solar irradiance and temperature distribution in different parts of the system during drying have been recorded. They dried grapes, figs, apples, green peas, tomatoes and onions conducted with and without storage materials. They reported that the quantity of the dried products was better when compared to open sun drying method. The results showed that the maximum temperature in drying chamber is about 60 °C.

Enibe [61] designed and evaluated a passive solar powered air heating system for the crop drying and poultry egg incubation consists of a single-glazed flat-plate solar collector integrated with a phase change material (PCM) heat storage system (Fig. 47). The PCM is prepared in modules, with the modules equispaced across the absorber plate. The spaces between the module pairs serve as the air heating channels, the channels being connected to common air inlet and discharge headers. The system was tested experimentally under daytime no-load conditions at Nsukka, Nigeria, over the ambient temperature range of 19–41 °C, and a daily global irradiation range of 4.9–19.9 MJ m^{-2}. These results showed that the system can be operated successfully for crop drying applications.

3.3.2. Solar drying system with auxiliary unit

3.3.2.1. Electric heating. Fig. 48 shows the schematics of the solar-assisted drying system. The system consists of the collector, the drying chamber, fan and the auxiliary heater.

Pratoto et al. [62,63] to develop a simple method for sizing solar-assisted natural rubber dryers is main aim. The drying system selected being simple. The only data required are monthly average solar heat gain and monthly average drying load. The thermal performance of air collectors indicates that configuration of collector array play an important role and to estimate the system performance. They showed that an empirical relation is performed by correlating the results of short-cut simulation to design parameters which are easily determined. The development consists in relating empirically the heat savings fraction to design parameters by simulations.

Tiris et al. [64,65] investigated and developed a multi-rack type mixed-mode solar dryer (Fig. 49) at the Ege University, Turkey. The drying consists of the collector, the drying chamber, rack, fan and the electrical heater. The results of this study showed that the

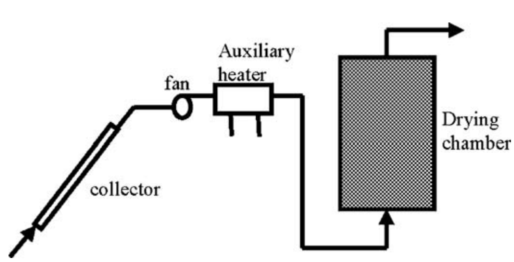


Fig. 48. Schematic representation of solar-assisted dryer system [62].

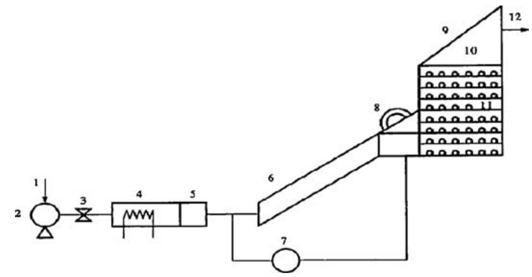


Fig. 49. Schematic diagram of a multi-rack type mixed-mode solar dryer (1. air inlet, 2. fan, 3.valve, 4. electrical heater, 5. flowmeter, 6. solar air heater, 7. pressure transducer, 8. pyranometer, 9. drying chamber, 10. rack, 11. products, 12. air outlet) [64].

drying curves of the solar dried products were compared with traditional sun drying results. The drying periods of solar dried sultana grapes, green beans, sweet peppers and chillies were 1.8, 2.2, 1.9 and 2.0 times shorter than the natural sun dried products (drying period: 6–10 days).

Pangavhane and Sawhney [34] reported in their review that Tsamparlis [110] studied a hybrid solar dryer (Fig. 50) for drying grapes, different fruits and vegetables. It consists of two units, the solar heating unit and the drying chamber. The heating unit has four flat-plate collectors and 20 evacuated tube collectors (Philips), organized in two units with 10 tubes and two flat-plate collectors in each unit. The solar air heating unit is detachable from the drying chamber. Using it for other heating applications when the dryer is not in use shortens its payback period. The drying chamber is the major component of the solar hybrid dryer. Its role is to modulate homogeneous drying conditions in the active drying space. It is divided into two parts; the upper part (Fig. 50a) consists of a fan, electrical heaters and the system for modulating the velocity field of the drying air. The lower part (Fig. 50b) contains trolleys with trays in which the fresh product is spread. The loading capacity for the grapes was 16–18 kg/m^2 in the trays. The drying operation was controlled by using dampers. The drying cabinet is metallic; whose sides are insulated using polyurethane foam. The 17 kW electric heaters are placed in the upper part of the drying chamber, with another 3 kW placed at the entrance of the solar pre-heated air. During the experiment, he found that in the hybrid solar dryer, the drying period of the grapes was reduced to 30–40 h [34]

Fig. 51 shows the schematics of the solar drying system. The system consists of the collector, the drying chamber, fan and the auxiliary heater. The solar collector is of the V-groove type and the collector area is about 15 m^2. An average output temperature of 50 °C can be achieved with a flow rate of 15.1 m^3/min and an average solar radiation of 700 W/m^2 and ambient temperature of 27–30 °C. A 10 kW auxiliary heat source has been used for

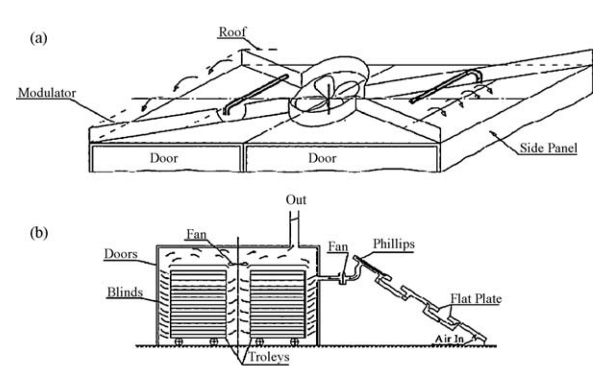


Fig. 50. The hybrid solar dryer: (a) heating unit and (b) drying chamber and solar air heater [34].

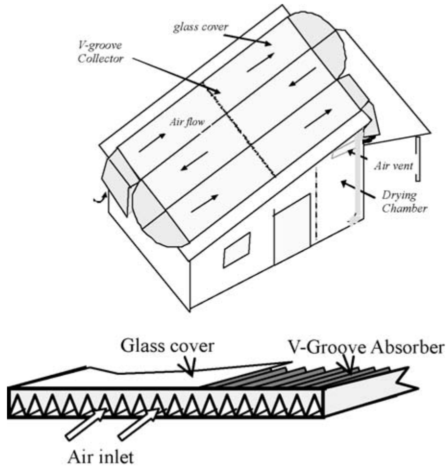


Fig. 51. Schematics of the solar-assisted drying system with the V-groove collector [66].

continuous operation and more effective temperature control. Experimental studies on the performance of a solar-assisted drying system on herbal tea, chillies, and noodles have been conducted [66].

The principal types of solar air heaters that can be coupled in solar drying system are: the single pass with front duct, single pass with real duct, single pass with double duct, and double pass solar air heater. It has been observed [67–69] that the double pass solar air heaters perform better than conventional single pass system. Wijeysundera et al. [67] concluded that two-pass designs perform better than the single-pass air heaters and reported an increase of 10–15% in collector thermal efficiency. In addition, the use of a double-pass resulted in an increase in the pressure drop a cross the collector. Mohamad [68] conducted theoretical studies of a double-pass solar collector with porous media in the second channel. Sopian et al. [69] performed the experimental studies on the performance of a double-pass solar collector with porous media in the second or lower channel. Fig. 52 shows the double-pass type solar collector. The second or lower channel of the solar collector is filled up with porous media which acts as heat storage system. This will increase the outlet temperature and the performance of the system. The collector width and length are 120 cm and 240 cm. The upper channel depth is 3.5 cm and the lower depth is 10.5 cm.

The system was tested for the drying of oil palm frond chips.

The solar drying system consists of solar air collector, blower, auxiliary-heater and drying chamber. The auxiliary heater is equipped with an on/off controller. The set temperature is 50 °C based on the temperature of the inlet to the drying chamber. Arranging this type of collector is not as simple as the V-groove single pass collector. The collector arrangement is shown in Fig. 53.

The system has been designed for drying of wet ground fronds from moisture content of 60% wet basis to 10% weight product and the drying time is not more than 10 h. The blower power rating was 0.11 kW, 230 V rotating at 2520 RPM. The collector was tilted at 15° from the horizon. The solar-assisted drying system using

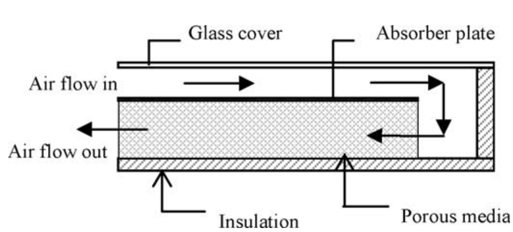


Fig. 52. The schematic of a double-pass solar collector with porous media in the second channel [69].

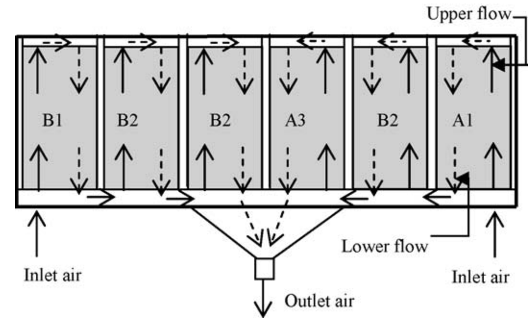


Fig. 53. The collector arrangement for the solar drying system.

double-pass solar collector with porous media can be used for drying oil palm fronds from moisture content of about 63% to moisture content of about 15%, for drying time of about 7 h. The system efficiency is about 25–30%. In addition, the auxiliary heater is used during unfavorable solar radiation conditions, especially in the morning and the evening [69–71].

Janjai et al. [72] studied experimental performance and modeling of solar drying of rosella flower and chilli using roof-integrated solar dryer (Fig. 54). The dryer consists of a roof-integrated solar collector and a drying bin with an electric motor (220 V, 1 phase, 0.373 kW) operated axial flow fan to provide the required airflow. The bin is connected to the middle of the collector through a T-type air duct. The roof-integrated collector consists of two arrays of collector: one facing the south and other facing the north with a total area of 108 m^2. These arrays of the collectors also serve as the roof of the building. The roof-integrated collector is essentially an insulated black-painted roof serving as an absorber, which is covered with a polycarbonate plate. The drying bin is essentially a deep bed batch dryer. The capacity of the dryer is 1.3 m × 2.4 m × 0.8 m and it is located inside the building. The

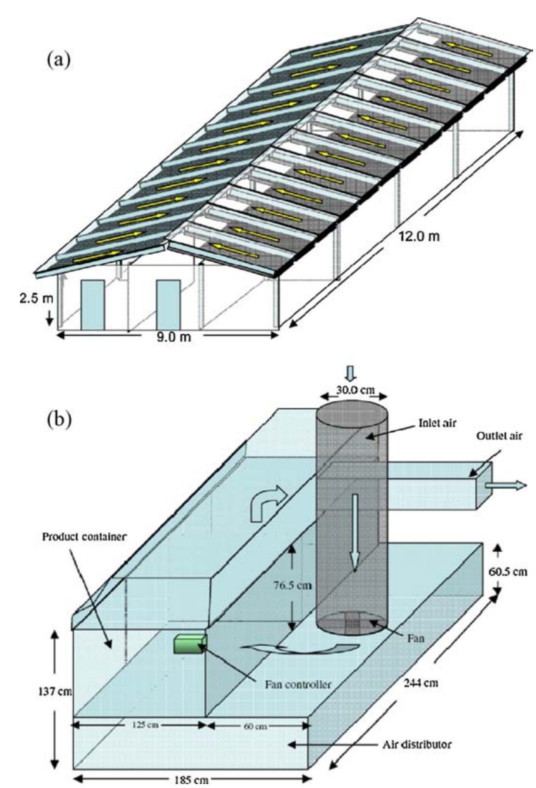


Fig. 54. (a) Roof-integrated solar drying system and (b) the drying bin [72].

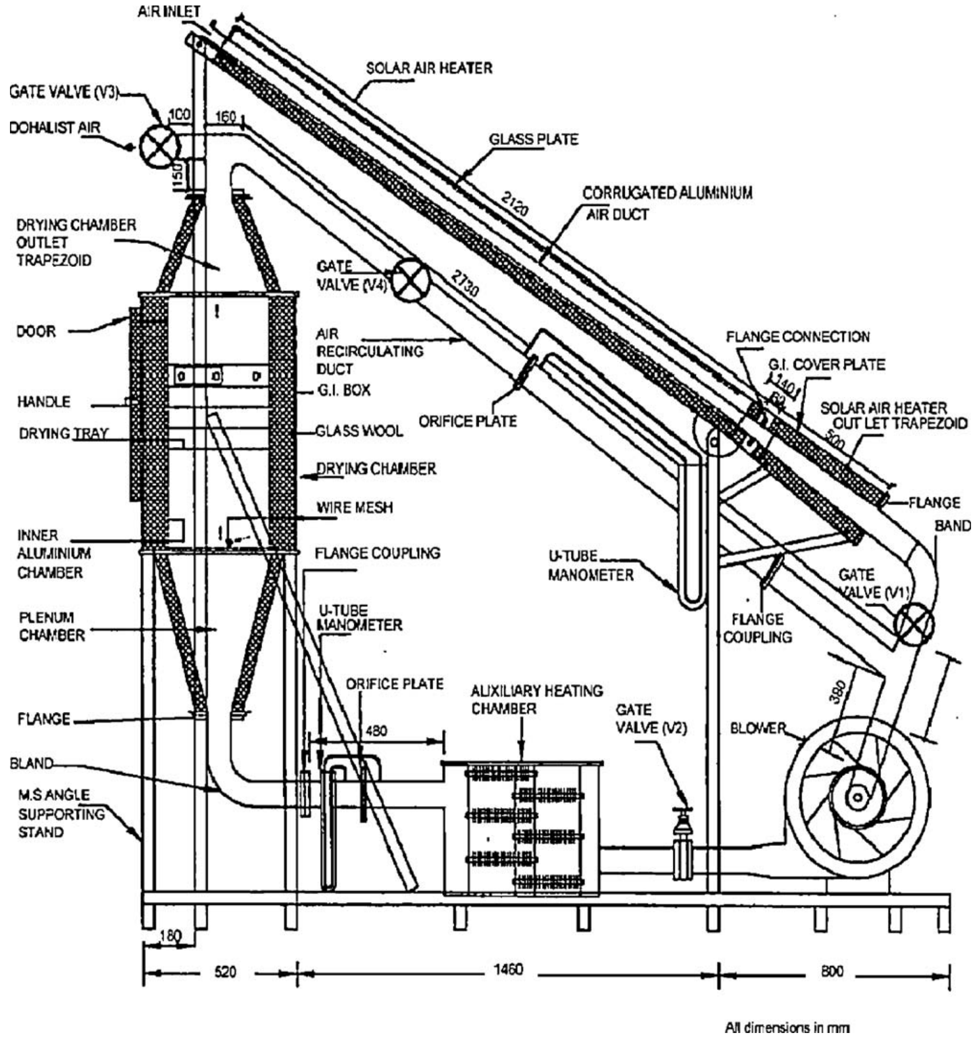


Fig. 55. Sectional details of solar-assisted forced convection dryer [73].

building was partitioned into one space for the drying bin and another two additional rooms. The first room was used for the preparation of the product to be dried and the second for the storage of dried products.

Sarsavadia [73] studied and developed a solar-assisted forced convection dryer (Fig. 55) for dehydration of onion slices for the controlled conditions of drying air temperatures and airflow rates similar to those employed in commercial onion dehydration. The dryer was also facilitated with recirculation of exhaust air. He reported that the total energy required for drying of onion slices increased with increase in airflow rate and decreased with increase in drying air temperature.

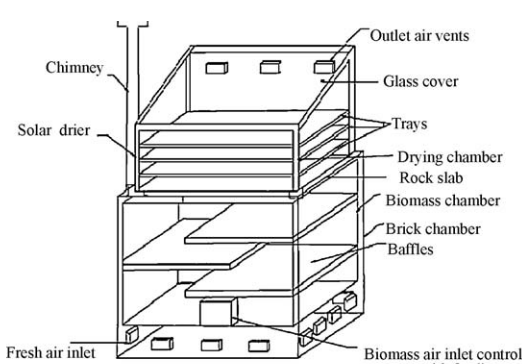


Fig. 56. Schematic diagram of solar biomass drier [74].

3.3.2.2. Biomass burner. Prasad et al. [74] developed a direct type natural convection solar drier integrated with a simple biomass burner (Fig. 56). The system was capable of generating an adequate and continuous flow of hot air temperature between 55 and 60 °C. The system is predestined for application on small farms in developing countries due to its low investment.

Bhattacharya et al. [75] designed, fabricated and tested a gasifier stove for the biomass-fuelled drying system, as shown in Fig. 57. A hybrid solar dryer consisted of an automatically controlled gasifier stove, a cross-flow heat exchanger, a drying cabinet located above the heat exchanger and a solar flat-plate collector. They reported that the required moisture content of banana and chilli were reached in the biomass-fuelled dryer within 18 and 22 h respectively, while they were required 66 and 48 h respectively for the natural sun drying. The maximum permissible temperature for fruits and vegetable drying is about 70 °C; the temperature of air entering the drying chamber should be controlled at this value.

Tarigan and Tekasakul [76] reported on the a mixed-mode natural convection solar dryer integrated with a simple biomass burner and bricks heat storage as back-up heating system (Fig. 58). The back-up heating system which can be constructed with easily available materials, tools and skills, can improve the viability of the

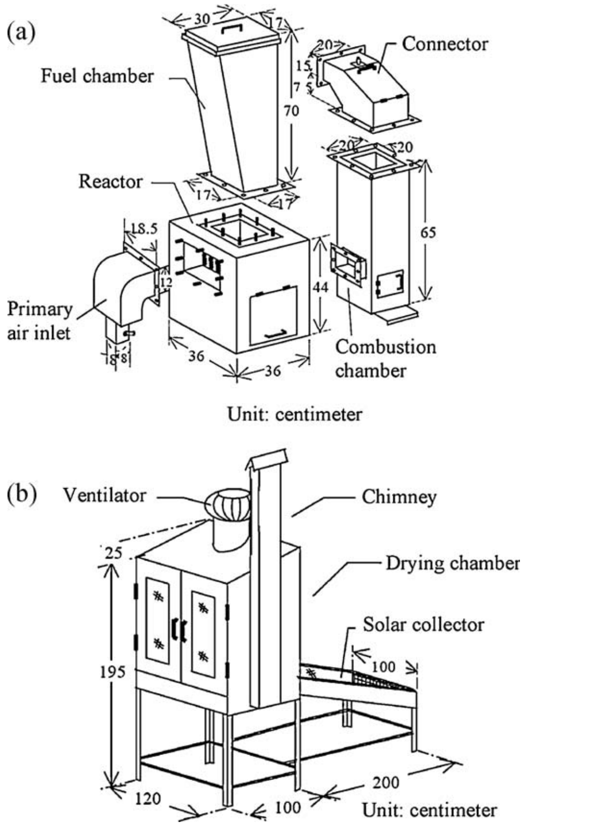


Fig. 57. Hybrid solar drying: (a) gasifier stove configuration and (b) drying chamber configuration [75].

dryer. The dryer was designed for small scale commercial producers of agricultural products in non-electrical locations in Thailand. From a series of evaluation trials of the system, the capacity of the dryer was found to be 60–65 kg of unshelled fresh harvested groundnuts. The drying efficiency of the solar component alone was found to be 23%. The efficiency of the burner with heat storage in producing useful heat for drying was found to be 40%. The key design features of the dryer contributed to produce an acceptable thermal efficiency, and uniformity of drying air temperature across the trays, were the jacket and gap enclosing the drying chamber and arranged bricks for storing heats.

Madhlopa and Ngwalo [77] designed, constructed and evaluated an indirect type natural convection solar dryer with integrated collector–storage solar and biomass-back-up heaters (Fig. 59). Simple materials and skills were employed to build it. The dryer was tested in three modes of operation (solar, biomass and solar–biomass), using 12 batches of fresh pineapples with each batch weighing about 20 kg, under different weather conditions. Meteorological conditions were monitored during the dehydration process.

3.3.2.3. LPG gas burner. Fig. 60 shows the experimental prototype direct hybrid solar dryer. It consisted of a 3.6 m × 3.6 m × 4.8 m scaled-down (1:4 scale) tobacco-curing barn with 1 tonne fresh leaves loading capacity, an array of 38.5 m^2 flat-plate solar air heaters, and a 6 m^3 rock-bed unit. Forced convection was induced through the system by one 1.5 kW and one 0.75 kW blower. LPG was used directly as an auxiliary heating fuel. It was found that an average fuel saving of 28 per cent was possible. The average overall airing thermal efficiency was found to be 40.5 per cent. The overall usefulness of a rock-bed thermal storage unit was still inconclusive.

Smitabhindu et al. [78] have been reported simulation and optimization of solar-assisted drying system (Fig. 61) for drying

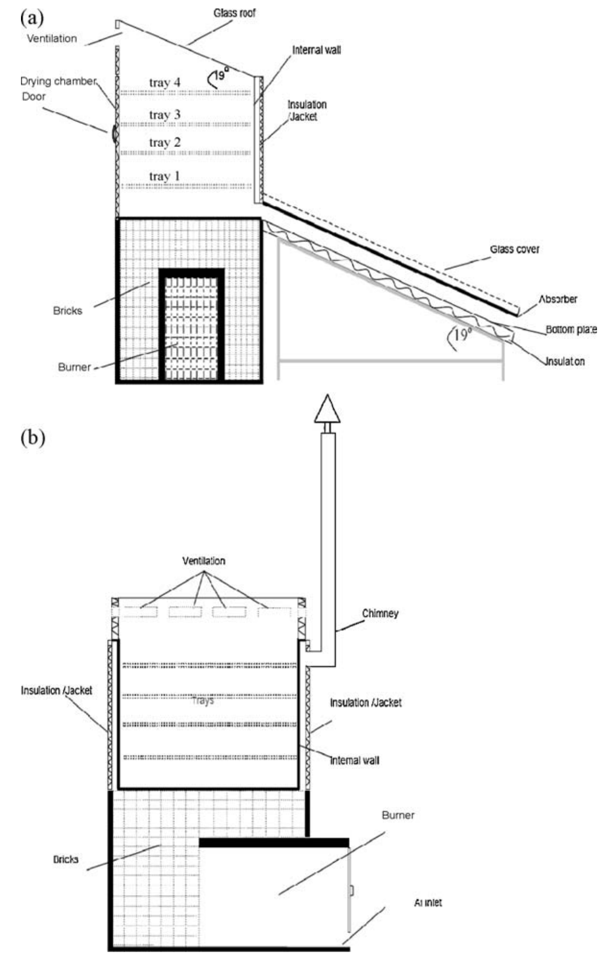


Fig. 58. Cross-section through the dryer: (a) side view and (b) back view [76].

bananas. The simulation model was validated by comparing the simulation results with the experimental results. The optimization problem was defined as the optimization of the geometry and operational parameters of the drying system so as to minimize the drying cost per unit of dried product. It results showed that the optimum values of the collector area and recycle factor were found to be 26 m^2 and 90%. These optimum values resulted in the minimum drying cost with 0.225 USD per kg.

3.3.2.4. Solar drying system with diesel engine. Fig. 62 shows a batch type solar dryer integrated with an electric motor (diesel engine) [111]. Pangavhane and Sawhney [34] reported in their review that

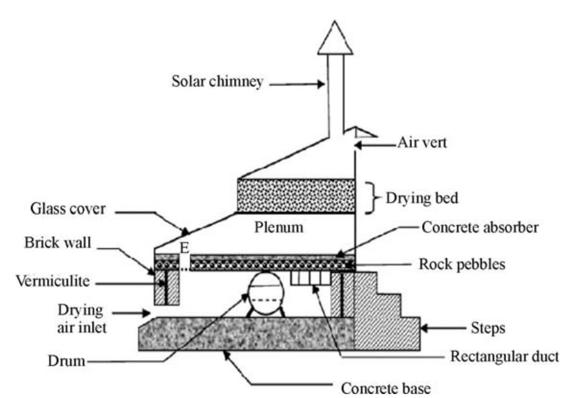


Fig. 59. Cross-sectional view of the solar dryer through the burner, collector, drying chamber and solar chimney [77].

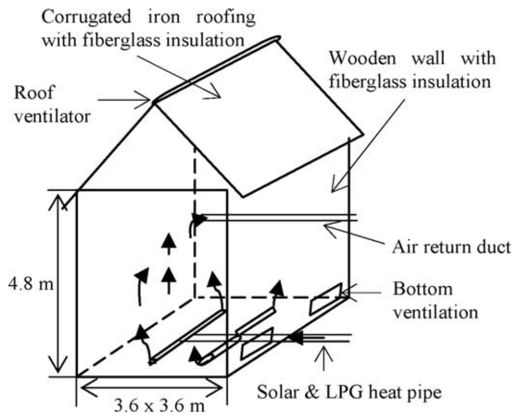


Fig. 60. The experimental prototype direct hybrid solar dryer [54].

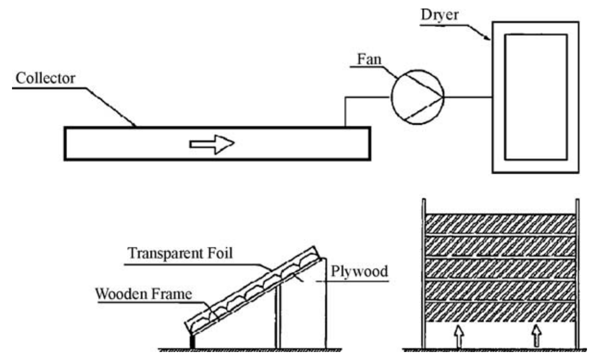


Fig. 62. Solar multiple layer batch dryer [111].

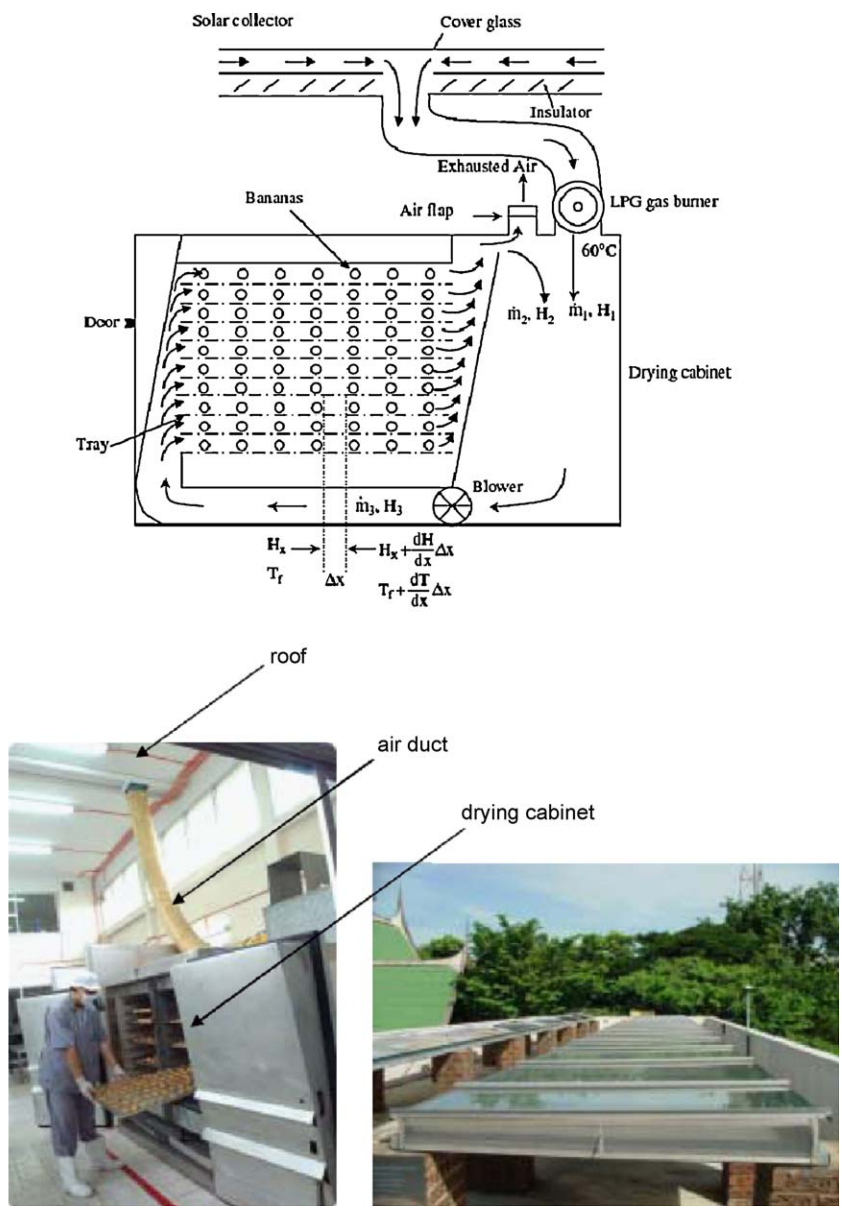


Fig. 61. (a) Schematic diagram of the solar-assisted drying system and (b) photograph of the drying cabinet inside the building and the solar collector on the roof of the same building [78].

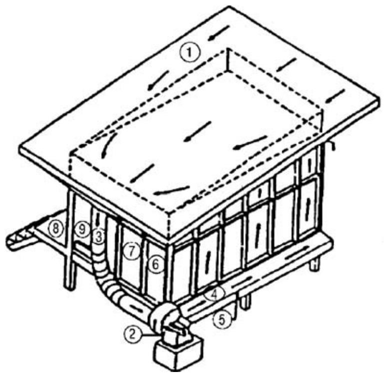


Fig. 63. A forced convection solar grain drying (1. flat-plate solar collector, 2. centrifugal fan, 3. air duct, 4. rectangular air duct, 5. sliding valve, 6. gypsum board 8 mm thick, 7. wall support, 8. rest floor, 9. sliding gate for unloading paddy) [54].

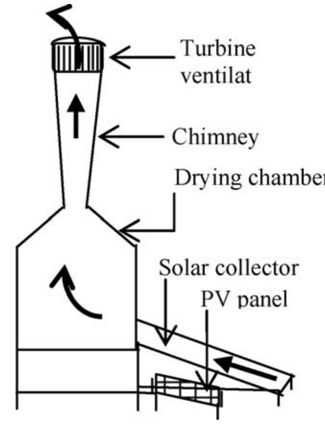


Fig. 65. Schematics of PV-assisted solar drying system [80].

the dryer consists of a flat-plate solar air collector, a fan and a multiple layer batch dryer. The air collector consists of a transparent foil cover and black corrugated metal absorber. The air was sucked underneath the absorber (instead of between the absorber and transparent cover) to prevent dust contamination on the absorber surface. The centrifugal fan was used to suck the air and was driven by an electric motor or diesel engine. Five wire mesh trays were installed in a container, which acted as a multiple layer batch dryer. The loading capacity of this dryer was 500 kg of fresh grapes per square metre of dryer surface or 38 kg of grapes per square metre of collector surface. The power required to drive the fan was 0.8 kW. The drying was completed within 5–6 days, i.e. the drying period was reduced 50% compared to natural sun drying. The product is completely protected from rain, dust and insect contamination [34].

Forced convection solar grain drying system was constructed and tested at a farmer's house in Nakorn Pathom province, Thailand (Fig. 63). The drying system consists of solar collector, a fan and diesel engine. The maximum loading of this dryer was 10 tons of paddy as reported by Soponronnarit [54].

3.3.3. Hybrid with geothermal or waste waters

Ivanova et al. [79] studied and developed the energy and economic effectiveness of a fruit and vegetable hybrid dryer (Fig. 64) at the University of Rousse, Bulgaria. The heating of the drying agent could use solar energy, geothermal or wastewaters, a conventional source, or both conventional and unconventional energy sources. Based on the experimental results, the saved energy by different schemes for energy supply is determined. Compared with the possibility of saving money from using solar energy and the heat utilized, the investment will be paid back within 2.4 years. The use of geothermal waters with temperature 68 °C secures 32.2% of the annual thermal load that has been determined to maintain the temperature of the drying agent 60 °C during day and night. The use of the solar energy during the day and hot geothermal or wastewater with temperature 68 °C during the night secures 26% of the annual thermal load.

3.3.4. Solar drying system with photovoltaic

The design and fabrication of the photovoltaic assisted solar drying system has been reported [80]. This drying system uses a custom designed parallel flow V-groove type collector. A fan powered by photovoltaic source assisted the airflow through the drying system. A funnel with increasing diameter towards the top with ventilator turbine is incorporated into the system to facilitate the airflow during the absence of photovoltaic energy source. The solar dryer also includes two 12 V, 1.2 A d.c.-fan attached to the intake of chimney. The configuration of the system is shown in Fig. 65. This drying system is designed with high efficiency and portability in mind so that it can readily be used at plantation sites where the crops are harvested or produced.

A daily mean efficiency about 44% with mean air flowrate 0.16 kg/s has been achieved at mean daily radiation intensity of 800 W/m^2. Daily mean temperature of air entering the drying chamber under the above condition is 46 °C. On a bright sunny day with instantaneous solar intensity about 600 W/m^2, the temperature of air entering the drying chamber of 45 °C has been measured. These study also showed that the air flow and air temperature increase with the increase of solar radiation intensities. In the absence of photovoltaic or in natural convection flow, the instantaneous efficiency decreased when solar radiation increased. The instantaneous efficiency recorded is 35% and 27%, respectively at 570 W/m^2 and 745 W/m^2 of solar radiation. The temperatures of drying chamber for the same amount of solar radiation are 42 °C and 48 °C, respectively. Thus, the solar dryer shows a great potential for application in drying process of agricultural produce.

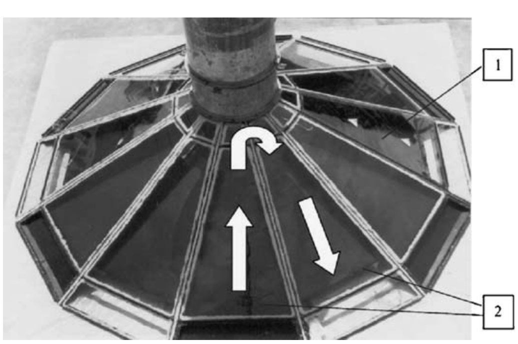


Fig. 64. General view of the combined dryer [79].

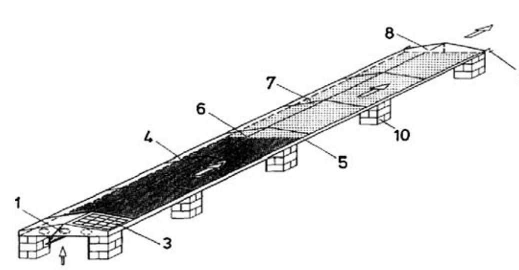


Fig. 66. Solar tunnel (1. fan, 2. inlet air, 3. solar cell module, 4. solar collector, 5. metal frame, 6. outlet of the collector, 7. drying tunnel, 8. outlet of drying tunnel, 9. rolling bar, 10. concrete block substructure) [81].

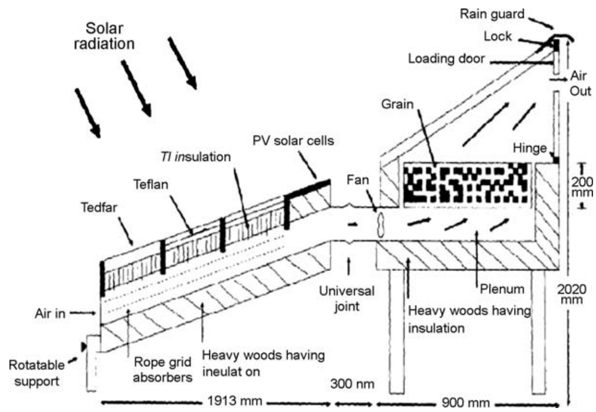


Fig. 67. Solar grain dryer incorporating a photovoltaic powered d.c. fan [84].

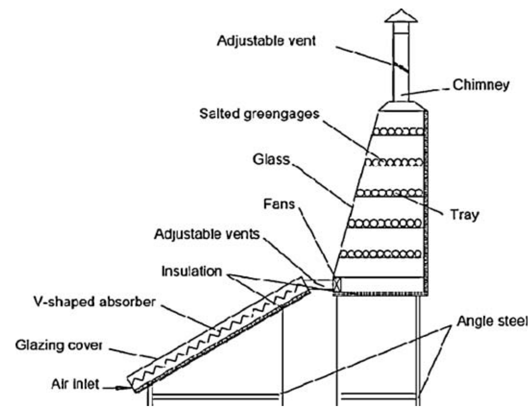


Fig. 69. Cross-section diagram of the examined solar drier [87].

Schirmer et al. [81] developed a multi-purpose solar tunnel dryer (Fig. 66). The dryer consist a plastic sheet-covered flat-plate collector, tree fans powered by a 53 W and solar cell module. The products to be dried were spread in one layer on a plastic net in the drying tunnel to receive energy from both the hot air supplied by the solar collector.

McDoom et al. [82] studied on the photovoltaic panel and storage batteries were able to comfortably run the blower continuously for 2 weeks and very poor weather conditions, the battery storage would power the system continuously for 2 days. Study has shown that 31% and 29% of energy can be saved in the production of dry coconut and cocoa, respectively.

Hanaa et al. [83] develops a new controlled drying method for drying of medical herb using a photovoltaic array and solar thermal system. The designed control technique ensures correct and continuous operation of the dryer's subsystems. A complete dynamic modeling of the solar thermal subsystem, using the energy balance principle, is developed. The results indicate the high effectiveness of the drying method.

A solar grain dryer incorporating photovoltaic powered air circulation (Fig. 67) designed and developed by Mumba [84,85]. The important feature in this new dryer was the use of photovoltaic solar cells incorporated in the solar air heater section to power a d.c. fan. This photovoltaic powered air circulation induces passive control over the drying air temperature. The dryer can dry 90 kg maize grain per batch from an initial moisture content of 33.3% dry basis to fewer than 20% dry basis in just 1 day. The controlled drying air temperature has an upper limit of 60 ± 3 °C to prevent grain overheating and cracking. Results from [84,85] showed that the incorporation of a PV-driven d.c. fan provided some form of passive control over the air flow and hence the drying air temperature. The dryer was coupled to a solar air heater having a sun-tracking facility and optimized blackened sisal rope grids for improved energy collection efficiency of the order of 80%. The dryer has been found to be cost-effective with a payback period of less than 1 year. Compared with the traditional sun drying method, drying with the dryer was found to be a viable option with many benefits, such as a protected drying environment, improved dried product quality and increased throughput. The drier is suitable for rural farm applications where grid electricity and fossil fuel are either nonexistent or extremely expensive for the average farmer.

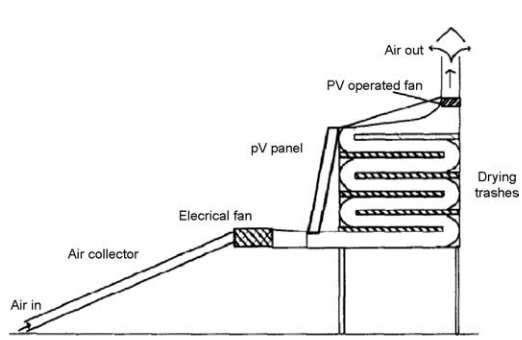


Fig. 68. The schematic scheme of the modular solar dryer [86].

Farkas et al. [86] studied analytical and experimental of a modular solar dryer for drying of apple (Fig. 68). The dryer consists of the a dyer (drying cabin) with different trashes for the different product, a photovoltaic module with the maximum power of 40 W, and an air solar collector with a transparent cover on the top and thermal insulation at the bottom side. The effect of the solar air collector module for the physical properties of drying air was studied along with the calculation of efficiency. They reported that the mass flow of the drying air through the system is one of the most important factor concerning to the whole process.

Li et al. [87] developed and examined a forced convection drier for drying salted greengages (Fig. 69). The dryer consisting of 6 m^2 of solar air collectors, a greenhouse-like drying chamber and three fans powered by a silica photovoltaic module of 20 W_p which was installed at the same tilt angle and orientation as the collectors. The air collector absorber is made of 0.5 mm aluminum sheets, is V-groove shaped and painted black matte. The experiment showed that the solar drying of the salted greengages was very effective, and the drying period was shortened to about 15 days from 48 days of the traditional sun drying. They also observed that using the solar drier could prevent regaining moisture by the salted greengages at night or in rainy days during the drying period. To improve the thermal efficiency, it is advisable to spread fully wet salted greengages on the top two meshes and semi-dry ones on other meshes of the drying chamber at the late stage of the drying process.

The application of solar energy can be broadly classified into two categories: thermal energy systems which converts solar energy into thermal energy and photovoltaic energy system which converts solar energy into electrical energy. The vital component in solar energy system is the solar collections systems. Two solar energy collection systems commonly used are the flat-plate collectors and photovoltaic cells. Normally, these two collection systems are used separately. It has been shown that these two systems can be combined together in a hybrid photovoltaic thermal (PVT) energy system. The term PVT refers to solar thermal collectors that use PV cells as an integral part of the absorber plate. The system generates both thermal and electrical energy simultaneously. The number of the photovoltaic cells in the system can be adjusted according to the local load demands. In conventional solar thermal system, external electrical energy is

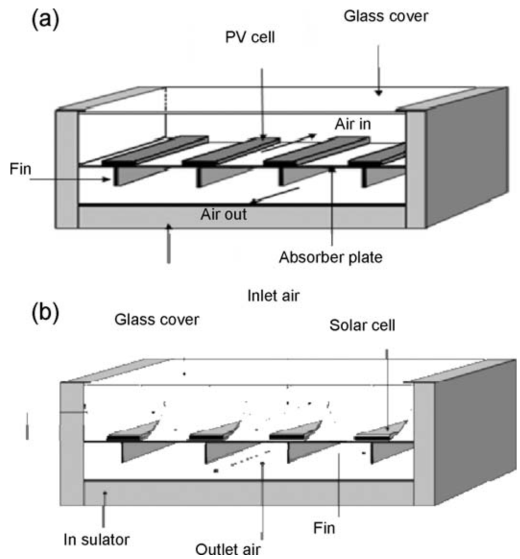


Fig. 70. Double-pass photovoltaic thermal solar collectors system with (a) fins and (b) CPC and fins [88].

required to circulate the working fluid through the system. The need for an external electrical source can be eliminated by using this hybrid system.

The first multiple-pass concept for the air cooled PVT systems suitable for drying system was introduced by Sopian et al. [88]. The technical development of the air cooled PVT systems can proceed in two directions. Firstly, simple single passed with photovoltaic panel as the absorber plate and relatively low combined photovoltaic thermal efficiency. Secondly, high efficiency, multiple-pass with some heat transfer augmentation features. The double-pass flow enhanced cooling of the photovoltaic cells and thus increasing the efficiency of the systems. The double-pass concepts was later extended to include heat transfer augmentation features such as a fins for enhancing heat removal by convective and conductive heat transfers and also compound parabolic collectors for solar radiation booster. The performance of the double-pass solar collector can be further increased by including these features. The intensity of the solar radiation incident upon the photovoltaic panel can be increase by installing a booster concentrator. Fig. 70 shows the basic design of the double-pass photovoltaic thermal solar collector with compound parabolic concentrator (CPC) and fins.

The air flowed through the first channel formed by the glass cover and the photovoltaic panel. Next it enters the second channel formed by the back plate and the photovoltaic panel. The first channel has compound parabolic concentrators to concentrate

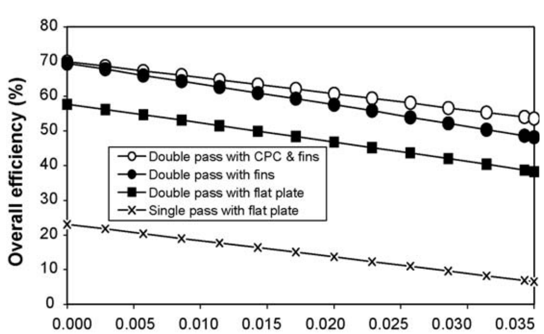


Fig. 71. Overall performance of PVT solar collector with single, double-pass system, double pass with compound parabolic solar collector and fins.

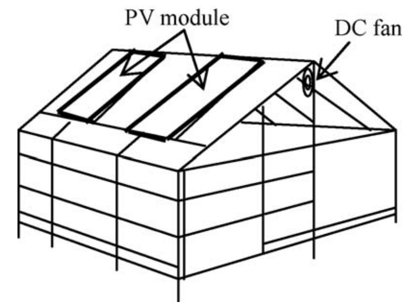


Fig. 72. Hybrid PVT integrated greenhouse dryer [92].

solar radiation. The second channel has fins that transfer the heat from the photovoltaic panel. This flow arrangement and the compound parabolic concentrators as well as the fins will increase heat removal from the photovoltaic panel and will enhance the efficiency of the system. Fig. 71 shows the performance of various PVT including single, double-pass system, double pass with compound parabolic solar collector and fins [88–91].

Barnwal and Tiwari [92] studied an experimental grape drying by using hybrid photovoltaic–thermal (PVT) greenhouse dryer (Fig. 72). The hybrid PVT integrated greenhouse dryer has been developed having floor area of 2.50 m $\times$ 2.60 m, 1.80 m central height and 1.05 m side walls height from ground and 30° roof slope. The greenhouse dryer has been integrated with two PV modules on south roof of the dryer. The PV module produces DC electrical power to operate a DC fan for forced mode operation and also provides thermal heating of greenhouse environment. To provide air movement in the greenhouse dryer, 0.15 m height is open at bottom side and further 0.10 m is provided with wire mesh. The air moves from bottom to top through three-tier system of perforated wire mesh trays as the air at bottom becomes hot. The UV stabilized polyethylene sheet has been fitted over the structural frame of the dryer which helps in trapping of infrared radiation. It also prevents unnecessary circulation of ambient air and thus maintains the desire temperature inside the greenhouse.

Tiwari and Sodha [93] studied an experimental validation of theoretical model of various configurations of hybrid PV/T air collector. They observed that glazed hybrid PV/T without tedlar gives the best performance.

3.3.5. Solar drying system with heat pump

Several solar-assisted heat pump dryer have been design, fabricated and tested. Hawlader et al. [94] studied the performance of the evaporator-collector and the air collector when operated under the meteorological condition of Singapore. They showed that "the evaporator- collector efficiency increases with increasing refrigerant mass flow rate. It was also revealed that the efficiency of the evaporator-collector is higher than that of the air collector". The maximum efficiencies of the evaporator-collector and the air collector were found about 86% and 75% respectively.

A solar-assisted heat pump dryer was used to dry poplar and pine timbers in heat pump timber dryer were experimentally analyses. Energy and exergy analyses were made for both types of timber and the timber drying performance of the heat pump dryer was evaluated. Energy analysis was made to determine the energy utilization. Exergy analysis was accomplished to determine of exergy losses during the drying process [95]. A heat pump dryer was designed, fabricated and tested to evaluate the drying characteristics of various herbs and the dryer performance under various conditions. Fatouh et al. [96] have been reported that the heat pump assisted dryer is recommended for industrial use. The system can be used successfully over wide ranges of air flowrate and supply air temperatures for drying operations.

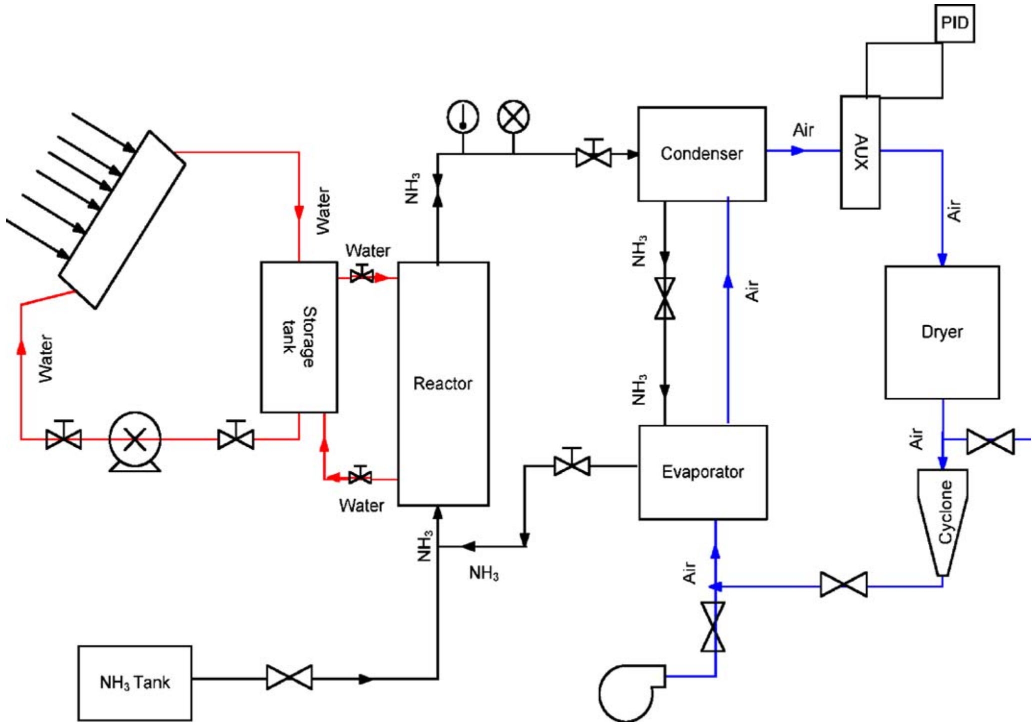


Fig. 73. Schematic diagram of solar-assisted chemical heat pump dryer [97].

3.3.6. Solar drying system with chemical heat pump

The schematics of a solar-assisted chemical heat is shown in Fig. 73 [97]. The system consists of four mean components solar collector (evacuated tubes type), storage tank, chemical heat pump unit and dryer chamber. In this study, a cylindrical tank is selected as a storage tank. The chemical heat pump unit contains of reactor, evaporator and condenser. In the chemical heat pump a solid gas reactor coupled with a condenser or an evaporator. The reactor contains a salt which reacts with the gas, the reactions used in this study is:

$$CaCl_2{\cdot}2NH_3 + 6NH_3 \rightarrow CaCl_2{\cdot}8NH_3 + 6\Delta Hr$$

The drying chamber contains multiple trays to hold the drying material and expose it to the air flow. The general working of chemical heat pump occurs in two stages: adsorption and desorption. The adsorption stage is the cold production stage, and this is followed by the regeneration stage, where decomposition takes place. During the production phase, the liquid-gas transformation of ammonia produces cold at low temperature in the evaporator. At the same time, chemical reaction between the gaseous ammonia and solid would release heat of reaction at higher temperature. The incoming air is heated by condensing refrigerant (ammonia) and enters the dryer inlet at the drying condition and performs drying. After the drying process, part of the moist air stream leaving the drying chamber is diverted through the evaporator, where it is cooled, and dehumidification takes place as heat is given up to the refrigerant (ammonia). The air is then passing through the condenser where it is reheated by the condensing refrigerant and then to the drying chamber. The material dried is lemon grass.

3.3.7. Solar-assisted dehumidification system

The temperature of air in drying process affects the quality, evaporation capacity as well as drying period. In addition, shorted time period is required for higher temperature drying. At higher temperature, pure water vapor pressure becomes higher; therefore, the difference between water vapor partial pressure and pure water vapor pressure becomes higher. This pressure difference is the driving force of water evaporation to the air. This driving force is directly proportional to the evaporation rate of water to air. However, drying at high temperature is not suitable for the materials which are sensitive to heat because it can cause cracks, browning which further reduce the taste of final product as well as the evaporation of the active ingredients such as in medicinal herbs.

A solar dehumidification system for medicinal herbs has been developed as shown in Fig. 74. The system consists of a solar collector, an energy storage tank, auxiliary heater, adsorbent, water to air heat exchanger, a water circulating pump, drying chamber, and other equipment. It is made up of essentially three processes, namely regeneration, dehumidification, and batch drying. During regeneration process, the air outside the dryer is heated with the heat exchanger and is supplied to the adsorbent. The adsorbent is heated with this hot air and water content rate is reduced, removing the water content. The water content is evaporated by the hot air and leaves the dryer. During dehumidification (adsorption) process, the air inside the dryer

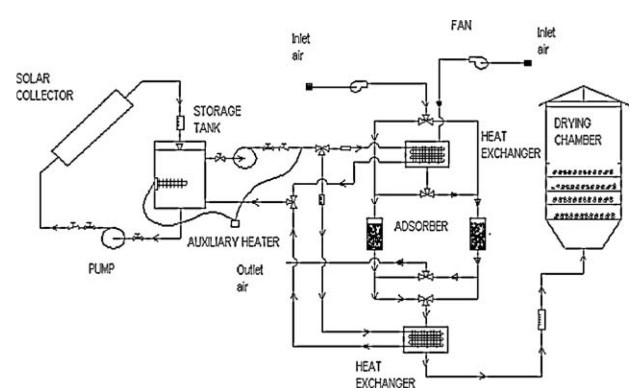


Fig. 74. Solar-assisted dehumidification system [98].

passes through the heat exchanger by use of the blower. However, since no hot water is circulated in the heat exchanger, the air reaches the adsorbent. The air is dehumidified with the adsorbent and is supplied the drying load as the dry air. The relative humidity and temperature of the drying chamber are 40% and 35 °C, respectively [98].

4. Solar drying of selected agricultural and marine products

4.1. Apple

Elicin and Sacilik et al. [31] has been developed a solar tunnel dryer (Fig. 23b) capable of dehydration of the apples. The moisture content was reduced from 82 to 11% in 32 h for the open sun drying, whereas the solar tunnel dryer took only 28 h. On base weather conditions, solar tunnel dryer resulted in a reduction in the drying time to an extent about 14% in comparison to open sun drying. The apple dried in the solar tunnel drier was completely protected from rain, insects, dust, bird, and the dried apple was a high quality in terms colour and hygienic.

4.2. Banana

Smitabhindu et al. [78] performed simulation and optimization of solar assisted drying system (Fig. 61) for drying bananas. The simulation model was validated by comparing the simulation results with the experimental results. The optimum values of the collector area and recycle factor were found to be 26 m^2 and 90% respectively with a minimum drying cost of 0.225 USD per kg.

Schimer et al. [81] developed a multi-purpose solar tunnel dryer (Fig. 66) to dry bananas in Thailand. They reported that "This dryer could be used to dry up to 300 kg of ripe bananas in each drying bath. They found that the temperature of the drying air from the collector varied between 40 and 65 °C during drying and bananas could be dried within 3–5 days, compared to the 5–7 days needed for open drying".

4.3. Cashew nut in shells

Mursalim et al. [17] modified cabinet dryer (Fig. 7) with natural convection system to dry Cashew Nut in Shells (CNS) in Indonesia. They reported that "solar dryer unit could heat dry air up to 78.7 °C maximum on ambient temperature of average 27.2 °C. Drying rate was 0.59% m.c/h, efficient of 64% and quality grade was a first class quality based on CNS standard in Indonesia".

4.4. Cassava

Forson et al. [24] designed a mixed-mode natural convection solar dryer (Fig. 14) and tested experimentally by drying cassava. Experiments revealed that 49.1, 65.9 and 162 kg of cassava could be dehydrated in 30–36 h with an expected average solar irradiance of 400 W/m^2, ambient conditions of 25 °C and 77.8% relative humidity.

4.5. Cauliflower

Kadam and Samuel [42] developed and tested a forced convection solar dryer using V-groove solar collector for drying cauliflower. The study was conducted to determine the thermal efficiency of the forced convective solar collector for drying cauliflower to obtain good quality dehydrated product. They found out Thermal efficiency of the solar heat collector directly depends on solar radiation and humidity in the air.

4.6. Chillies

Chillies have a higher moisture content to be removed and can be dried at a higher temperature. A collector flow rate of 40 m^3/h m^2 will produce a higher temperature rise of up to 30 °C which would give a total temperature of 60 °C. Chillies require more energy for drying and each square meter of solar panel will dry approximately 3 kg of chillies a day assuming a 50% drying efficiency. A higher air flow with lower temperature rise could be used with a longer time in the drier. Solar panel efficiency would increase and each square meter of solar panel would be able to dry 4 kg of chillies a day from 80% moisture content to 5% [99].

Hossain and Bala [100] developed a multi-purpose solar tunnel dryer. It can be used to 80 kg of fresh chillies. They concluded that "In all the cases, the use of this drier led to considerable reduction in drying time in comparison to that of conventional sun drying, and the products dried using this drier were of better quality as compared to their conventional sun dried counterparts. Average air temperature rise in drier was about 22 °C above the ambient temperature and it was almost constant in the drier". The chillies dried in the solar tunnel dryer were completely protected from rain, dust, birds, rodents, dirt and microorganisms. The solar tunnel drier is recommended for drying of both red and green chillies. As well, Hossain et al. [101] built simulation and economic model for drying system of chillies for optimum designs. The design geometry is found to be sensitive to cost of major construction material of the collector, solar radiation and air velocity in the drier.

4.7. Copra

A forced convection solar drier (Fig. 35) designed, fabricated and tested to dry copra by Mohanraj and Chandrasekar [47]. They reported that this drying is more suitable for producing high quality copra for small holders. About 75% of high quality copra could be produced. Unlike with kiln and sun drying, the copra obtained was free from smoke, dust, bird and rodent damage. "The average thermal efficiency of the solar air heater was estimated to be about 24%. Drying copra in the drier reduced its moisture content from about 52% to 8% and 10% in 82 h for trays at the bottom and top, respectively. The maximum drying air temperature recorded during peak sunshine hours was 63 °C. The average temperature reduced to 31 °C outside the hours of sunshine and during the night".

4.8. Cocoa

McDoom et al. [82] reported that "the case of cocoa in the continuous venting mode, the moisture content reduced from 98 to 8% dry basis in 18 h with the heater on- time being 12 h. For a similar load and moisture content reduction of cocoa the total drying time for intermittent venting mode was 14 h while the heater on- time was 9 h giving an energy saving of 29%".

Hii et al. [106] studied quality of cocoa beans dried using a direct solar dryer at different loadings (20, 30 and 60 kg). They reported that "overall quality assessment showed that the 20 kg treatment was able to produce reasonably good-quality beans as compared to other loadings and therefore is recommended for direct solar dryer".

4.9. Coconut

McDoom et al. [82] reported that "the reduction of moisture content of coconut using the continuous venting mode from 60 to 7% dry basis took 28 h with the heater on for the full duration of the drying period. A similar reduction in moisture content of coconut

took place in 34 h with the heater on for 18.8 h and approximately 7/8 of the air being recycled. The energy saving realized here is 31%".

4.10. Figs

El-Sebali et al. [7] found that the moisture contain decrease from initial value of about 70% to final value of 20% after 32 h and 12 h when figs are dried in full size with drying without storage and with storage material (sand).

Gallali et al. [102] studied chemical analysis and sensory quality (color, texture and flavor) for the dried fruits and vegetables using open sun and solar drying (mixed and indirect-mode). They reported that "Figs moisture was reduced to 23.5% using mixed-mode drying and 46.9% in case of open sun for the same period".

4.11. Grapes

Pangavhane and Sawhney [34] have reviewed solar dryers for grape drying. Pangavhane et al. [25] developed a multipurpose natural convection solar dryer (Fig. 15). They reported that "the drying airflow rate increased with increase in ambient temperature by the thermal buoyancy in the collector. The collector efficiencies of this natural convection solar dryer were ranged between 0.26 for 0.0126 kg/s and 0.65 for 0.0246 kg/s; which were sufficient for heating the drying air. In this study, grapes were dried and the qualitative analysis showed that the traditional drying of grape, i.e. shade drying and open sun drying required 15 and 7 days, respectively, while the natural convection solar dryer took only 4 days and produced better quality raisins. The drying time of the grapes is also reduced by 43% compared to the open sun drying. The developed natural convection solar dryer could produce the average temperature between 50 and 55 °C, which was optimum for dehydration of the grapes as well as for most of the fruits and vegetables".

Gallali et al. [102] reported that the mixed and indirect modes of drying were more effective than open sun, since the final moisture contents for grapes were about 13, 20 and 68%, respectively.

4.12. Green peas

El-Sebali et al. [7] reported that 1 kg of green peas can be dried at 45.5–50.5 °C for 8–10 h to a final moisture content of 5% in an indirect type natural convection solar dryer.

4.13. Mango

Madhlopa et al. [23] reported that sliced fresh mangoes having an initial moisture content of 85 can be dried at 31.7–40.1 °C for 20 h to a final moisture content of 13% in an indirect type natural convection solar dryer (Fig. 13). It was found that the dryer was suitable for preservation of mangoes and other fresh foods. Toure and Kibangu-Nkembo [103] reported that mango having an initial moisture content of 84 can be dried with maximum temperature allowable at 40 °C for 15 h to final moisture content of 27.6% in type of natural convection solar dryer.

4.14. Onions

El-Sebali et al. [7] reported that moisture content (M_t) decreases from its initial value M_o (85%) to 57% and M_t (6%) after 48 and 32 h for the full size and cut samples, respectively, under the same conditions of RUN2 (with storage but without chemical pretreatment). The moisture contents of the chemically treated onions reach 46% and (6%) after 24 h for the full size and cut samples, respectively.

Hybrid solar drier (Fig. 55) was designed, fabricated and tested by Sarsavadia [73]. For drying of onion slices from initial moisture content of about 86% (w.b.) to final moisture content of about 7% (w.b.), the total energy required per unit mass of water ranged between 23.548 and 62.117 MJ/kg water during without using any recirculation of air. The percent energy contribution by the solar air heater, electrical heater, and blower to the total energy requirement ranged between 24.5% and 44.5%, 41.0% and 66.9%, and 8.6% and 16.3%, respectively. The total energy required for drying the onion slices ranged between 12.040 and 38.777 MJ/kg water for the experiments conducted using partial recirculation of exhaust air. The percent contribution to the total energy required by the solar air heater, electrical back-up heater, and blower ranged between 22.4% and 40.9%, 33.6% and 62.6%, and 11.2% and 37.2%, respectively. Total energy decreased with increase in fraction of air recycled. The maximum savings in total energy up to 70.7% can be achieved with recycling of the hot exhaust air [73].

4.15. Paddy

Exell has been developed a low-cost mixed-mode natural convection solar dryer (chimney-type solar dryer) for drying paddy (Fig. 17). This dryer is discontinuous-type solar dryer, based on natural convection. Paddy could be dried safely in 2–3 days. Igbeka [104] have presented a method of evaluation and comparing three different solar dryers, solar concentrator/dryer (Dryer 1), flat-plate collector solar dryer with in-bin storage (Dryer 2) and drying chamber with chimney (Dryer 3). Paddy was used as reference product. He found that the drying efficiency were about 18%, 30% and 58% for Dryer 1, Dryer 3 and Dryer 3, respectively. The air temperature difference recorded from Dryer 1 was the highest, but Dryers 2 and 3 were found to be more effective than Dryer 1.

A forced convection solar drier (Fig. 30c) was constructed and tested to dry paddy at a farmer's house in Thailand as reported by [54]. The system consists of the collector, drying bin and blower. This dyer was 4.48 m long, 3.74 m wide, solar air heater and a vertical fixed bed drying-bin having a capacity of 12 tonnes of paddy. Drying tests indicated that one tonne of paddy could be dried from a moisture content about 17% to 14% in 1–4 days depending on weather conditions. Average electrical energy consumption for a blower was estimated to be 7 kWh per drying batch. Economic analysis showed that the solar dryer was economical when reduction of paddy loss was accounted for, but was much less attractive when the benefit only came from better price of dry paddy [54].

As well, Soponronnarit [54] reported a forced convection hybrid solar dryer (Fig. 63) to dry paddy in Thailand. When an engine was used to drive the fan, it required, on average, 16 l of diesel oil per tonne of paddy per one per cent wet-basis of moisture removed. The corresponding drying rate was 0.5 per cent wet-basis per tonne of dry paddy per hour. The maximum storage capacity was 10 tonnes. Economic analysis, assuming that benefits were derived from reduction of loss and better price of paddy, showed that this drying was economical only for a paddy field where two crops were cultivated every year. The cultivation area should be 1.44–4.32 ha. The payback period was 2.3–14.8 years.

4.16. Pineapple

Hybrid solar drier (Fig. 59) was designed, constructed and evaluated to dry pineapple by Madhlopa and Ngwalo [77]. They reported that the thermal mass was capable of storing part of the absorbed solar energy and heat from the burner. It was possible to dry a batch of pineapples using solar energy only on clear days.

Drying proceeded successfully even under unfavorable weather conditions in the solar–biomass mode of operation. In this operational mode, the dryer reduced the moisture content of pineapple slices from about 669 to 11% (d.b.) and yielded a nutritious dried product. The average values of the final-day moisture pickup efficiency were 15%, 11% and 13% in the solar, biomass and solar–biomass modes of operation, respectively. It appears that the solar dryer was suitable for preservation of pineapples and other fresh foods.

Bala et al. [105] was designed, constructed and evaluated hybrid solar drier (Fig. 65) to dry fresh pineapple of 150 kg. They reported that this dryer was completely protected from insects, rain and dust and product was a high quality product. They found that maximum air temperature of drying air at the collector outlet was 64 °C.

4.17. Rosella flower

n Saeed et al. [108] studied the effects of drying conditions on the drying behaviour of Roselle (*Hibiscus sabdariffa* L.). The experiments were conducted in Constant Temperature and Humidity Chamber. Four temperatures (35, 45, 55, and 65 °C) and five relative humidities (30, 35, 40, 45, and 50%RH) were studied. Drying air temperature was found to be the main factor affecting the drying kinetics of Roselle; raising the drying temperature from 35 to 65 °C dramatically reduced the drying times. The effect of the relative humidity was lower than that of temperature; increasing the relative humidity resulted on longer drying times. Higher equilibrium moisture contents were obtained with high relative humidities and low temperatures. Furthermore, drying was observed only in the falling-rate period. Statistical analysis was carried out and comparison among drying models was made to select the best-fitted model for the drying curves. Among twelve tested models, the two-term exponential model was found to be superior to the other models in terms of fitting performance.

4.18. Strawberry

El-Beltagy et al. [44] reported that the indirect solar dryer was successfully tested under weather conditions of Minufiya, Egypt, where high quality dried strawberry was obtained. The performance of the solar collector to heat the drying air is assumed satisfactory; it could raise the ambient temperature to around 47 °C at peak conditions which is considered adequate for strawberry drying.

4.19. Tea

A hybrid solar drier (Fig. 65) designed, fabricated and tested to dry tea in Malaysia by Ruslan et al. [80]. They reported the total energy required to maintain a drying chamber temperature of 50 C is 60.2 kWh. The auxiliary energy contribution is 17.6 kWh. Hence, solar energy contributes 42.6 kWh during the process and contributes approximately 70.2% of the overall energy requirement. To further decrease the weight to 2.86 kg, further drying is required. The drying process is continued until 20:00 and the contribution of solar energy in the total energy requirement dropped to 56.3%. Green tea (*Camellia sinensis*) or herbal tea differs from black tea because it undergone minimal oxidation during processing. Green teas varieties can differ substantially due to variable growing conditions, processing and harvesting time. Green tea contains many organic compounds and the processing requirements differ depending on specifications on the types of tea to be produced. The aroma of the herbal tea depends on the method of drying since chemical reaction continues during the drying process. Discoloration of herbal tea will occur if the drying process is delayed. Higher temperature drying will result in lost of the essential ingredient in tea suitable for medicinal properties. Drying of green tea has been conducted using the solar dryer with the V-Groove type solar collectors as shown in Fig. 51. For best results, the fresh tea leaves are dried from an initial moisture content of 87% (wet basis) to 54% (wet basis) at a drying temperature of 50 °C and flow rate of 15.1 m^3/min [109].

4.20. Tobacco

Soponronnarit [54] reported hybrid solar dryer (Fig. 58) in Thailand. "The loading capacity of the dryer was 1000 kg of fresh tobacco leaves. His results indicated that solar energy accounted for 25–30 per cent of the total energy consumed. Thermal efficiencies of tobacco-curing drying were estimated to be 36–40%, or in terms of energy consumption per kg, of 12.3–13.2 MJ/kg water evaporated for tobacco-curing. On the basis of the benefit derived from LPG fuel saving, it was shown that the benefit/cost ratio of solar-assisted tobacco-curing was 0.63. The payback period for the latter case was 7 years.

4.21. Tomatoes

El-Sebali et al. [7] reported that moisture content (M_t) decreases from its initial value M_o (95%) to 85% and M_t (7%) after 36 h and 28 h for the full size and cut samples, respectively, under the same conditions of RUN2 (with storage but without chemical pretreatment).

4.22. Turmeric rhizomes

Hybrid solar dryer for drying of turmeric rhizomes was evaluated and developed by Prasad et al. [74]. The system (Fig. 56) is capable of generating an adequate and continuous flow of hot air temperature between 55 and 60 °C. Turmeric rhizomes were successfully dried in developed system. They found that open sun drying had taken 11 days to dry the rhizomes while solar biomass drier hybrid took only 1.5 days and produced better quality produce. The efficiency of the whole unit obtained was 28.57%. The system is predestined for application on small farms in developing countries due to its low investment.

4.23. Fish

N'Jai [32] tested three different types of natural circulation greenhouse dryers for drying fermented fish (Fig. 24) with used species bonga (shads), croakers, threadfin, mackerel and catfish. He reported that solar dryers produce well-dried products with reasonably long storage life. Solar dryers for fish, however, should not be introduced in isolation. Other parameters, which are integral aspects of the drying process and effectively contribute to losses, improved salting, better packaging and storage method, and proper sanitary conditions are areas to be looked into and developed. Diouf [33] also presented three different types of dried fish using natural circulation greenhouse dryers (Fig. 25). He reported analysis of technical and socioeconomic aspects of the artisanal fish processing sector. The results shows that implementation and operation of solar drying facilities by fishery technologists and experienced processors represents real progress in applied research on artisanal fish technology in Senegal.

4.24. Oil palm

Malaysia was the world's largest producer and exporter of palm oil and accounts for more than 60% of global export. Palm oil was

Table 3
Advantages and disadvantages of the types of solar dryers.

Classification	Advantages	Disadvantages
Passive dryers	+ Simplest + Low capital and running costs	Low capacity
Active dryers	+ Independent of the ambient climatic conditions + Short drying periods than passive dryers	More complex and expensive than passive dryers
Hybrid solar dryers	+ Allow better control of drying + Ability to operate without sun reduce of product loss +May be faster than passive and active dryers	Expensive, and may cause fuel/gas dependence

Table 4
Sample prices of solar dryers.

Type	Fig. No.	Price (US$)	Author(s)
Direct solar cabinet dryer (passive)	Fig. 3	14	Lawand [10]
PAU domestic (passive)	Fig. 6	36	Singh et al. [16]
Passive mixed-mode	Fig. 12a	152	Simate [22]
Passive indirect-mode	Fig. 12b	220	Simate [22]
Mixed-mode type forced convection solar tunnel dryer (active)	Fig. 40	939	Usub et al. [53]
Hybrid solar dryer	Fig. 61	5333	Smitabhindu et al. [78]
Hybrid solar dryer	Fig. 66	6000	Schirmer et al. [81]

extracted from oil palm fruits in the mills. The waste products of oil palm mills are empty fruit bunches, fibers, shells and fronds. There were about 145 oil palm trees per hectare in Malaysia. About 25 pieces of fronds can be obtained from a single tree. The average weight of each frond was about 8 kg. Hence, about 200 kg of fronds can be obtained in a year per tree. Hence, about 30 tons of fronds can be produced in one hectare in a year. Some of the palm fronds have to be cut to facilitate the harvesting of the fruit bunches. The fronds can be converted in useful products. One way was to chip and then dry them to be used as feed stock for animal feed. The solar assisted-drying system using double-pass solar collector with porous media (Figs. 52 and 53) can be used for drying oil palm fronds from moisture content of about 63% to moisture content of about 15%, for drying time of about 7 h. The system efficiency is about 25–30%. In addition, the auxiliary heater was used during unfavorable solar radiation conditions, especially in the morning and the evening [69].

4.25. Pegaga leaf

Pegaga leaf (*Centella Asiatica* L.) is an ethnomedical plant and medicinal herb used in different continents by diverse ancient cultures and tribal groups that is sensitive to heat. Its medicinal properties have been ascribed to the active principles: asiatic acid, asiaticoside, madecassic acid and madecassoside. Yahya et al. [107] was studied the drying kinetics and quality (color degradation) of the pegaga leaf by varying the inlet air temperature and relative humidity using a solar assisted dehumidification drying system (Fig. 74). It can be concluded that for the drying of pegaga leaf, there are two distinct falling rate periods at lower relative humidity that become less at higher relative humidity. The drying rate curves also become more convex at lower temperature and higher humidity. The color of pegaga leaf dried using the environmental chamber becomes darker as the air temperature is increased to 65 °C. On the other hand the color of pegaga leaf dried using solar assisted dehumidification drying system does not become darker due to the lower air temperature of less than 56 °C and the lower relative humidity of less than 36% used in the solar assisted dehumidification drier. This solar drying system is therefore suitable for drying of pegaga leaf without significant loss of quality because of the lower temperature and relative humidity used.

5. Conclusions

The use of solar drying for agricultural and marine products has a large potential from the technical and energy saving point of view. Numerous types of solar dryers have been designed and developed in various parts of the world, yielding varying degrees of technical performance. Table 3 illustrates the general categories of solar dryers along with advantages and disadvantages of each. Table 4 gives examples of several solar driers and the possible price for local manufacture.

In conclusion the technical directions in the development of solar-assisted drying systems for agricultural produce are compact collector design, high efficiency, integrated storage, and long-life drying system. Air-based solar collectors are not the only available systems. Water-based collectors can also be used whereby water to air heat exchanger can be used. The hot air for drying of agricultural produce can be forced to flow in the water to air heat exchanger. The hot water tank acts as heat storage of the solar drying system.

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